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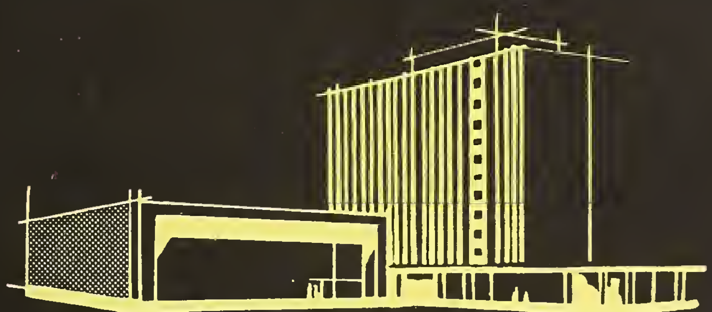

Interrelations Between Cement & Concrete Properties

PART 5

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards

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Interrelations Between Cement and Concrete Properties, Part 5

Freezing-and-Thawing Durability, Saturation, Water Loss and Absorption, Dynamic Modulus

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This publication is dedicated to the memory of Mr. Raymond L. Blaine, who passed away during its preparation. The death of Mr. Blaine brings deep regret to all those associated with him on this project, as well as throughout his career at the National Bureau of Standards. Mr. Blaine was the guilding light and motivating force of this tremendous undertaking for almost twenty years. His inspiration and leadership spanned the period from the project's inception, acquisition of the cements, testing of the cements and concretes, analysis of the data, and publication of most of the results. For this and for his many other accomplishments and contributions in the field of cement and concrete research, including development of the Blaine Air Permeability Fineness Meter, he will long be remembered by colleagues throughout the world.

Abstract

The concretes described in earlier parts of this series were subjected to laboratory freezing and thawing tests, and measurements were made of the weight loss, dynamic modulus, durability factor, and number of cycles required to reach 40 percent reduction in dynamic modulus. Companion specimens were subjected to drying and subsequent soaking in the laboratory and to dynamic modulus tests at various ages and moisture conditions. The effect on these properties of a large number of variables connected with chemical and physical properties of the cements and with properties of the concretes was studied by multivariable regression techniques. Air content of the concretes and degree of saturation generally had the greatest effect on the measurements. In general, minor constituents and trace elements did not show significant relationships with the measured properties, but there was evidence that some of the variables, such as alkali content, water cement ratio, slump, and possibly setting time might have influenced durability through an effect on the air-void system. Specimens stored in the fog room after the freezing-and-thawing tests generally regained most or all of their original dynamic modulus. There were significant differences between cements with respect to regain of dynamic modulus (autogenous healing), with the non-air-entraining cements gaining more than the air-entraining cements, on the average.

Key words: Absorption; autogenous healing; durability factor; dynamic modulus of elasticity; saturation coefficient.

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Contents

Section 11. Freezing and Thawing Durability of Concrete

R. L. Blaine and H. T. Arni*

The concretes described in earlier parts of this series were subjected to laboratory freezing and thawing tests, and measurements were made of the weight loss, dynamic modulus, durability factor, and number of cycles required to reach 40 percent reduction in dynamic modulus. The degree of saturation achieved during soaking before freezing and thawing was also measured. The results were analyzed to determine which of several variables connected with chemical and physical properties of the cements plus variables connected with the concretes were significant as independent variables in multivariable regression analyses of these measurements. The air content of the concrete was the significant independent variable. Higher percentages of dicalcium silicate (C_2S), K_2O, and MgO were associated with a lower durability factor. An increase in tricalcium aluminate (C_3A) and tetracalcium aluminoferrite (C_4AF) were associated with greater weight loss at 40 percent reduction in dynamic modulus. There was evidence that some of the variables, such as alkali content, water-cement ratio, slump, and possibly setting time, might have influenced durability through an effect on the air-void system. Specimens stored in the fog room after the freezing-and-thawing tests generally regained most or all of their original dynamic modulus, with the non-air-entrained concretes generally gaining more than the air-entrained concretes. There were also significant differences between cements in the amount of autogenous healing.

Key words: Autogenous healing; durability factor; freezing-and-thawing tests; modulus regain; portland cement; saturation ratio; trace elements; weight loss in freezing-and-thawing tests.

Contents

1. Introduction

It has been well established in both laboratory and field tests that concrete made with air-entraining cements, or with hydraulic cements with air-entraining agents added at the time of mixing have, among other properties, greater resistance to damage by freezing and thawing than concretes made without air-entraining agents. Bogue [1][1] reported that "no consistent relation was found between the composition and fineness of the cements and the behavior of concrete exposed to freezing and thawing." This statement was based on reports on the Portland Cement Association Long-Time Study on Cement Performance in Concrete [2].

Grieb and Werner [3] in their further study of concretes made of the cements used in the Long-

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[1] Figures in brackets refer to literature references at the end of this section (p. 38).

Time Study concluded that "concrete prepared with cements having tricalcium aluminate (C_3A) content of more than 10 percent had poorer durability than concrete made with cements having C_3A contents of less than 10 percent." Mather [4] reported on freeze-thaw tests on concretes made of the same cements but with an air-entraining agent added and found all highly resistant to damage by freezing and thawing. Oleson and Verbeck [5] found "no evidence of a significant effect of cement composition or fineness, per se, on concrete performance" (when concrete specimens made of these cements were stored outdoors at the Illinois Test Plot for more than 25 years).

Laboratory tests for evaluation of resistance to freezing and thawing are normally made with specimens which have not been permitted to dry [6], whereas concretes in structures usually (but not always) have a period when some of the water evaporates before being subjected to freezing. In concretes that have not been permitted to dry, the size and spacing of small bubbles of entrained air have been shown to be of paramount importance [7.] Concrete specimens that have been allowed to air-dry take some time to become saturated to the extent that they are damaged by the freezing of the water in the concrete.

Various criteria have been used to evaluate the effects of freezing and thawing on concrete. Among these are loss of compressive or flexural strength, loss of weight, and expansion of the concrete resulting from repeated freezing and thawing.

Hornibrook [8] found that when specimens were left in the thawing water for several days after a freezing-and-thawing cycle, an increase in resonant frequency occurred which was attributed to autogenous healing. Such autogenous healing of concrete partially damaged by freezing has not been fully explored. Present test methods [6] require that concrete specimens be kept in a frozen condition when the sequence of freezing and thawing cycles is interrupted.

The present investigation was undertaken to determine whether the chemical composition of the cements was associated directly or indirectly with the durability factor calculated from freezing-and-thawing tests or with weight loss of concrete which had been partially air dried and then resoaked prior to freezing. In view of the fact that the degree of saturation of the concrete plays such and important role in the results of freezing-and-thawing tests, studies were made of the factors associated with a calculated saturation ratio of the concretes. Studies were also made to determine the extent of recovery of the dynamic modulus of concretes (autogenous healing) after the freezing-and-thawing tests had been completed. Because of the limited quantities of the various cements available it was not possible to make additional tests with air-entraining agents added.

2. Materials

2.1. Cements

The cements used in this investigation have previously been described. The frequency distributions of the results of chemical analyses as well as spectrochemical analyses were reported in part 1, sections 2 and 3, of this series of articles [9], and other tests with these cements have been reported in parts 2, 3, and 4 [10, 11, 12]. Most of the 199 commercial portland cements were obtained from different areas of the United States, but a few came from other countries. The cements were classified as to type on the basis of chemical and physical properties.[2]

2.2. Aggregates

The coarse and fine aggregates are described in part 1, section 1 [9] of this series of papers. A high quality, 1-in maximum size, rounded, quartzite, coarse aggregate (White Marsh) and a sand from the same source were used for making the concretes. The fineness modulus of the sand was 2.82, of the coarse aggregates 6.82, and of the combined aggregates 4.82.

3. Methods of Test

3.1. Preparation of Concretes

The details of the proportioning and mixing of the concretes were described in part 1, section 1, of this series of articles [9].

Two series of concretes were made with these cements. One series (Series O) was made with a constant water/cement ratio of 0.635. A second series (Series A) was made in which the water content was changed, if necessary, to obtain a concrete with a 5 ± 1-in slump. In the two series, the cement-to-aggregate ratio was the same. The cement factor varied to some extent from the nominal 5½ bags of cement per cubic yard, primarily because of variations of the entrained and entrapped air.

3.2. Test Specimens

Eight 3- × 4- × 16-in specimens were made from each of the cements, four in each of the two series of concretes. These were made from the same batches of concrete as those used for the 6- × 8- × 16-in specimens used for shrinkage and

[2] On the basis of this classification, there were 82 Type I, 8 Type IA, 68 Type II, 3 Type IIA, 20 Type III, 3 Type IV, and 12 Type V cements.

expansion tests [12]. The specimens were cast in steel molds in accordance with ASTM Designation C 192–52T procedures [13] except that the molds were lined with sheet plastic and no oil or grease was used. Two of the 3- by 4- by 16-in specimens were subjected to laboratory freezing-and-thawing tests, and the other two were placed in the field for natural weathering tests.

3.3. Storage of Specimens

The 3- × 4- × 16-in concrete specimens were covered with moist burlap for the first 20 to 24 hours, then removed from the molds and placed in a fog room at 100-percent relative humidity (RH). At the age of 14 days, the specimens were removed from the fog room and stored on end in laboratory air at 73 °F and 50-percent relative humidity for 4 weeks. After this drying period, the two specimens from each batch which were to be subjected to laboratory freezing-and-thawing tests were placed in water at 40 °F. After 24 hours soaking the freezing-and-thawing tests were started. The weight, fundamental resonant frequencies, and dynamic Young's modulus of elasticity (dynamic E) were determined at 1 and 14 days, at the time just prior to placing in the 40 °F water, at the start of the freezing cycle, and at periodic intervals during the freezing-and-thawing tests. The fundamental transverse resonant frequencies were determined in accordance with ASTM Designation C 215 [14]. After completion of the freezing-and-thawing tests the specimens were placed in the fog room at 100-percent RH, and resonant frequency measurements were again made after storage periods ranging from approximately one to five years.

3.4. Freezing-and-Thawing Cycles

The two duplicate concrete specimens from each concrete batch were frozen in water at 0 °F and thawed in water at 40 °F with each cycle completed in two hours in accordance with ASTM Designation C 290 [15]. The freezing and thawing tests were continued until there was a 40 percent reduction in dynamic modulus.

The calculations of dynamic Young's modulus of elasticity took into account the weights of the specimens and the fundamental resonant frequencies, but no corrections were made for possible variations of Poisson's ratio nor for dimensional changes caused by sloughing of the specimens. In other words, instead of the ratio of the squares of the resonant frequencies being used as suggested in C 290, the following formula was used for relative dynamic modulus:

$$P_c = \frac{W_1 n_1^2}{W n^2} \times 100$$

where P_c = relative dynamic modulus of elasticity, percent, after c cycles of freezing and thawing

W = weight at 0 cycles of freezing and thawing

W_1 = weight after c cycles of freezing and thawing

n = resonant frequency at 0 cycles of freezing and thawing, and

n_1 = resonant frequency after c cycles of freezing and thawing.

3.5. Durability Factor

Durability factors (DF) were calculated using the formula given in ASTM Designation C 290 based on a termination of the tests at 300 cycles of freezing and thawing or 60 percent relative dynamic modulus. In many instances, with the concretes made with air-entraining cements, the freezing-and-thawing tests were continued past 300 cycles in order to obtain the 40 percent reduction in dynamic modulus. The values for the two duplicate specimens from each series were averaged.

3.6. Saturation Ratio

The saturation ratio was calculated from the weight lost during 28 days drying in laboratory air, the weight gained during 24 hours soaking at 40 °F (prior to freezing and thawing), and the volume of air measured in the plastic concrete. The weight lost during drying and the weight gained during soaking, in grams, were taken as the water gained and lost in ml. The percentage of air, determined gravimetrically in the plastic concrete, multiplied by the volume of the specimens in ml was taken as the volume of air in the plastic concrete. The measured volume of air plus the volume of water lost during drying was taken as the total volume of air voids in the hardened concrete available to take up water. The ratio of the volume of water gained during soaking to the total volume of air voids is the saturation ratio. These values were considered as the degree of saturation at the start of the freezing-and-thawing tests. The ratios ranged from about 0.4 to 0.8 for non-air-entrained concrete and 0.2 to 0.4 for air-entrained concretes.

3.7. Recovery of Dynamic Modulus After Freezing-and-Thawing Tests

Autogenous healing of the concrete specimens after freezing-and-thawing tests was evaluated by studying the ratio of dynamic modulus after various periods of moist storage following the freezing-and-thawing tests.

4. Abbreviations

The abbreviations, notations, etc., used in this section for chemical and physical properties of the cements are the same as those used in previous sections of this series of articles.[3]

In this section, the prefix "O" of the four-letter titles for the various dependent variables refers to the concretes of Series O in which a water/cement ratio (w/c) of 0.635 was used. The prefix "A" refers to the second series of concretes in which the water was readjusted, if necessary, to give a 5 ± 1-in slump. The abbreviations for the dependent variables used in this section are as follows:

For Series O concretes made with a w/c of 0.635

ODUR = durability factor of concrete specimens which had been air-dried then subjected to rapid freezing and thawing in water.

OWTL = weight loss of concrete specimens at the time of 40 percent loss of dynamic modulus expressed as percent of weight at 0 cycles of freezing and thawing.

OSAT = ratio of volume of water absorbed in 24 hours (prior to start of freezing test) to possible absorption.

OAIR = air content in percent by volume

OCYS = number of freezing-and-thawing cycles required to cause a 40 percent reduction in dynamic modulus.

For Series A concretes having a 5 ± 1-in slump, the letter "A" is used instead of "O" as ADUR, AWTL, ASAT, AAIR, and ACYS for the different variables.

5. Statistical Analyses

The statistical techniques used to find and evaluate the independent variables associated with the durability factor, weight loss, saturation, and dynamic modulus ratios have been described in a previous section of this series entitled "Materials and Techniques" [9]. The statistical treatment was the same as that used in all previous sections of this series of articles. Multiple regression equations were calculated by the method of least squares using various independent variables. As in previous sections, equations were calculated for both AE + NAE cements and NAE cements. Comparisons were made using only commonly determined variables and also using these together with minor and trace elements.

Ratios of reduction in variance to original variance ("F" ratios) obtained by fitting equations were calculated for two kinds of cases: (1) for equations including one or a few main independent variables as compared to the original data on the dependent variable, or (2) for equations in which additional independent variables were included as compared to a previous equation with fewer variables[4]. The "F" ratios and critical "F" values which, when equalled or exceeded, indicate significance at the $\alpha = 0.05$ and $\alpha = 0.01$ levels are summarized in table 11–27.

After it had been determined which independent variables were significantly associated with the dependent variable when used in an equation, the residuals of the equation were fitted by the method of least squares to other single independent variables and the reduction in variance calculated. If any of the additional independent variables indicated a significant reduction in variance, they were tried in the equation and retained if the coef./s.d. ratio was greater than 1.0.

Equations were also computed for the "odds" and "evens" in the array of cements. Comparisons were made of the coefficients of the variables in the two groups of cements, and these were compared to the coefficients and coef./s.d. ratios computed for all the cements.

Although freezing-and-thawing tests were made on all 199 cements, the calculations of the equations presented in this article were limited to those for which trace elements had been determined.

Equations presented in this article were selected from a large number of trial equations indicating the calculated relationship of various independent variables to durability and degree of saturation. These equations were selected primarily to indicate the association with dependent variables of commonly determined variables having coef./s.d. ratios greater than 1.0 when used in multivariable equations, and also to indicate which of the minor and trace elements might have had an effect.

Some of the limitations on interpretations of multivariable regression equations have been discussed in part 1, section 1, subsections 4.2, 4.3, and 5 [9]. Other limitations and problems of interpretation have also been discussed in other sections of this series of articles.

[3] These abbreviations include the use of C_3A, C_3S, C_2S and C_4AF for the calculated potential compounds, tricalcium aluminate, tricalcium silicate, dicalcium silicate, and tetracalcium aluminoferrite, respectively. Insol for insoluble residue, Loss for loss on ignition, APF for air permeability fineness, and Wagn for Wagner turbidimeter fineness are also used. AE + NAE refers to airentraining plus non-air-entraining cements, and NAE to the non-air-entraining cements.

[4] Statistical terms and notations employed in this section are the same as those used in previous sections of this series of articles. For example, S.D. refers to the estimated standard deviation calculated from the residuals of a fitted equation, or the estimated standard deviation about the average. Also, as in previous sections, s.d. refers to the estimated standard deviation of a coefficient of an independent variable used in a fitted equation. The term coef./s.d. is the ratio of the estimated coefficient (of an independent variable used in an equation) to its estimated standard deviation. "DF" designates degrees of freedom. As indicated in previous sections, a coef./s.d. ratio greater than 1.0 was considered to be of sufficient significance to warrant further investigation.

TABLE 11–1. *Frequency distribution of cements with respect to durability factor of concretes having a nominal 5 ½ bags cement per cubic yard and a water-cement ratio of 0.635 (ODUR)*

Type cement	Durability factor										
	0 to 10	10 to 20	20 to 30	30 to 40	40 to 50	50 to 60	60 to 70	70 to 80	80 to 90	90 to 100	Total
	Number of cements										
I	10	23	28	16	3	2					82
IA							1	4	2	1	8
II	12	22	25	5	2	2					68
IIA									3		3
III	4	5	4	3	2	2					20
IIIA									3		3
IV, V	4	8	3								15
Total	30	58	60	24	7	6	1	4	8	1	199

6. Results of Tests

6.1. Durability Factor

6.1.1. Durability Factor of Series O Concretes

The frequency distribution of the durability factors of concretes made with a water-cement ratio of 0.635 (ODUR) is presented in table 11–1. The concretes made with air-entraining cements Types IA, IIA, and IIIA all had higher durability-factor values than did those made with the non-air-entraining cements. There was a fairly broad distribution of values and there was an overlapping of the values of the concretes made with different types of NAE cements. Eighty percent of the non-air-entrained concretes had durability factors below 30, while all of the air-entrained concretes had durability factors greater than 60.

Equations selected from those computed to determine the various independent variables associated with the durability factor are presented in table 11–2. The use of the air content in eq 1, or the saturation coefficient at the start of the freezing-and-thawing tests (OSAT) in eq 2, as independent variables each resulted in a highly significant reduction in variance. (See table 11–27). With the use of the air content and the additional use in equation 3 of C_3S, C_2S, Na_2O, K_2O, MgO and fineness, all commonly determined independent variables, there was a significant reduction in variance. Of the trace elements, Ba, Rb, Pb, Ti, and Cu had coef./s.d. ratios greater than 1.0 when used with commonly determined independent variables in the multivariable regression equation as indicated in eq 4. Use of the trace elements in the equation resulted in a highly significant reduction in variance. (See table 11–27). In eqs 4A and 4B, calculated for the "odds" and "evens" in the array of cements, Pb and Cu, as well as C_3S and fineness had coef./s.d. ratios less than 1.0 in one or the other of the smaller groups of cements[5].

Equations 5 and 6, calculated using SiO_2 instead of C_3S and C_2S, also resulted in a reduction in variance significant at the 1.0 percent level. The use of the trace elements in addition to the commonly determined variables in eq 6 resulted in a significant reduction in variance. (See table 11–27). In the equations for the "odds" and "evens" (eqs 6A and 6B) fineness, Ba, and Pb had coef./s.d. ratios less than 1.0 in one or the other of the smaller groups of cements.

Equations calculated for the NAE cements are presented in table 11–3. The coefficients for the air content and saturation coefficient in eqs 1 and 2 respectively were highly significant, but the coef./s.d. ratios were lower than when the AE cements were included as in table 11–2. The coefficients for the other independent variables in eqs 3, 4, 5, and 6 of table 11–3 are in reasonable agreement with those of the previous table. Using commonly determined variables in eqs 3 and 5 resulted in highly significant reductions in variance, and the use of trace elements in eqs 4 and 6 each resulted in highly significant reductions in variance as a result of the added independent variables. It may noted, however, that in equations for the "odds" and "evens" eqs 4A, 4B, 6A, and 6B, C_3S, Na_2O, fineness, Ba, and Pb had coef./s.d. ratios less than 1.0 in one or the other of the equations for the smaller groups of cements.

The estimated contributions and ranges of contributions to the durability factor of the various independent variables calculated from the coefficients of eq 4 table 11–3 are presented in table 11–4. The ranges of the independent variables were assumed to be the same as for all 199 cements previously described in sections 2 and 3 of this series [9]. An increase in air content of the NAE cements resulted in an increase in the durability factor. Increase in C_3S, K_2O, MgO, fineness, Rb, Ti, and Cu was associated with a decrease in the durability factor. The coefficients of C_3S, Na_2O, Ba and Pb were of doubtful significance as the coef./s.d. ratios were less than 2.0.

[5] As has been indicated in previous sections, chance occurrence of two or more extreme values in one of the two groups may cause such anomalous results. Another possible contributing factor was the assignment of zero to values for trace elements having less than the lowest reported value.

TABLE 11–2. *Coefficients for equations for AE + NAE cements relating the freeze-thaw durability factor for concretes of nominal 5½ bags of cement per cubic yard and a water-cement ratio of 0.635 to various independent variables (ODUR)*

Eq. No.	Note		Const.	Air content	C_3S	C_2S	SiO_2	Na_2O	K_2O	MgO	APF	Ba	Rb	Pb	Ti	Cu	OSAT	S.D.
1	1	ODUR	= +8.577	+8.241														11.18
		s.d.	= (1.306)	(0.490)														
2	1	ODUR	= +101.4														−127.6	13.24
		s.d.	= (6.3)														(10.4)	
3	1	ODUR	= +80.01	+8.901	−0.5263	−0.9197		−7.211	−22.84	−1.932	−0.00207							9.72
		s.d.	= (23.93)	(0.448)	(0.2968)	(0.2735)		(4.562)	(4.08)	(0.707)	(0.00156)							
4	1	ODUR	= +88.58	+8.887	−0.5301	−0.8174		−8.258	−20.29	−2.750	−0.00306	−40.24	−1068	−208.3	−14.05	−209.5		9.14
		s.d.	= (22.92)	(0.426)	(0.2847)	(0.2626)		(4.329)	(4.24)	(0.690)	(0.00149)	(21.59)	(416)	(116.6)	(6.01)	(83.5)		
4A	2	ODUR (odd)	= +42.69	+8.785	*−0.0299	−0.4100		−7.159	−13.48	−2.758	*−0.00082	−38.79	−892	−240.2	−13.71	*−111.9		9.46
		s.d.	= (33.81)	(0.658)	(0.4017)	(0.3828)		(5.921)	(6.51)	(1.057)	(0.00225)	(36.07)	(557)	(134.0)	(7.68)	(118.6)		
4B	3	ODUR (even)	= +127.59	+9.126	−0.9782	−1.1383		−11.135	−26.98	−2.911	−0.00469	−44.98	−1492	*−136.6	−10.95	−290.2		9.05
		s.d.	= (33.75)	(0.601)	(0.4629)	(0.3934)		(6.891)	(6.18)	(0.986)	(0.00226)	(29.80)	(698)	(309.3)	(10.56)	(133.1)		
5	1	ODUR	= +98.20	+8.929			−3.108	−8.246	−24.05	−2.176	−0.00162							9.73
		s.d.	= (18.97)	(0.447)			(0.690)	(4.492)	(3.97)	(0.677)	(0.00152)							
6	1	ODUR	= +98.20	+8.899			−2.589	−8.758	−20.85	−2.886	−0.00285	−39.31	−1095	−204.3	−14.44	−216.1		9.12
		s.d.	= (17.88)	(0.425)			(0.661)	(4.260)	(4.15)	(0.655)	(0.00145)	(21.50)	(413)	(116.2)	(5.97)	(82.5)		
6A	2	ODUR (odd)	= +78.54	+8.788			−2.093	−8.381	−16.72	−3.111	*−0.00052	*−34.83	−952	−227.5	−15.82	−159.8		9.56
		s.d.	= (26.29)	(0.665)			(0.961)	(5.938)	(6.27)	(1.045)	(0.00227)	(36.37)	(561)	(135.2)	(7.66)	(116.1)		
6B	3	ODUR (even)	= +117.06	+9.121			−3.000	−10.370	−27.01	−2.703	−0.00520	−45.61	−1428	*−148.3	−11.04	−289.5		9.01
		s.d.	= (25.96)	(0.598)			(0.984)	(6.661)	(6.15)	(0.895)	(0.00201)	(29.61)	(683)	(306.7)	(10.51)	(132.5)		

Note 1, 179 cements, Avg. = 25.44, S.D. = 17.97
Note 2, 90 cements
Note 3, 89 cements
*Coef./s.d. ratio less than 1.0.

TABLE 11–3. *Coefficients for equations for NAE cements relating the freeze-thaw durability factor of concretes of nominal 5 ½ bags cement per cubic yard and a water-cement ratio of 0.635 to various independent variables (ODUR)*

Eq. No.	Note		Const.	Air content	C_3S	C_2S	SiO_2	Na_2O	K_2O	MgO	APF	Ba	Rb	Pb	Ti	Cu	OSAT	S.D.
1	1	ODUR	= +15.25	+3.957														10.85
		s.d.	= (2.02)	(1.113)														
2	1	ODUR	= +58.93														−60.88	10.18
		s.d.	= (6.16)														(10.02)	
3	1	ODUR	= +82.38	+5.436	−0.4817	−0.8846		−4.690	−19.75	−2.089	−0.00253							9.55
		s.d.	= (24.29)	(1.057)	(0.3024)	(0.2775)		(4.617)	(4.21)	(0.712)	(0.00158)							
4	1	ODUR	= +93.54	+6.830	−0.5456	−0.8319		−7.094	−19.34	−2.866	−0.00346	−37.03	−883	−190.6	−14.72	−176.9		9.13
		s.d.	= (23.82)	(1.062)	(0.2964)	(0.2712)		(4.480)	(4.42)	(0.713)	(0.00154)	(21.87)	(427)	(116.9)	(6.26)	(85.8)		
4A	2	ODUR (odd)	= +81.12	+7.513	*−0.3122	−0.5951		−8.208	−14.80	−2.839	−0.00541	−46.87	−895	*−351.1	−13.95	−185.9		9.06
		s.d.	= (32.82)	(1.540)	(0.4153)	(0.3769)		(5.693)	(6.57)	(1.058)	(0.00205)	(25.38)	(622)	(444.2)	(10.51)	(113.9)		
4B	2	ODUR (even)	= +93.15	+6.863	−0.5990	−0.9809		*−4.199	−24.34	−2.996	*−0.00130	*−48.32	−890	−137.2	−11.83	−183.3		9.56
		s.d.	= (37.84)	(1.660)	(0.4569)	(0.4263)		(8.364)	(6.86)	(1.126)	(0.00255)	(52.76)	(677)	(134.0)	(8.57)	(143.9)		
5	1	ODUR	= +102.92	+5.596			−3.074	−5.923	−21.25	−2.359	−0.00207							9.57
		s.d.	= (19.04)	(1.053)			(0.693)	(4.541)	(4.08)	(0.682)	(0.00155)							
6	1	ODUR	= +102.86	+6.933			−2.623	−7.643	−19.96	−3.000	−0.00330	−36.56	−917	−187.3	−15.24	−185.0		9.12
		s.d.	= (18.26)	(1.046)			(0.676)	(4.387)	(4.29)	(0.672)	(0.00150)	(21.81)	(422)	(116.5)	(6.19)	(84.3)		
6A	2	ODUR (odd)	= +97.47	+7.602			−2.139	−9.112	−16.25	−3.057	−0.00505	−45.71	−972	*−320.5	−14.32	−202.3		9.03
		s.d.	= (24.35)	(1.529)			(0.913)	(5.547)	(6.26)	(1.009)	(0.00198)	(25.24)	(610)	(440.3)	(10.46)	(111.0)		
6B	2	ODUR (even)	= +106.71	+7.102			−3.126	*−5.527	−24.64	−3.174	*−0.00105	*−47.03	−937	−135.4	−13.19	−189.3		9.52
		s.d.	= (31.02)	(1.614)			(1.114)	(8.087)	(6.81)	(1.080)	(0.00251)	(52.51)	(671)	(133.4)	(8.27)	(142.8)		

Note 1, 168 cements, Avg. = 21.80, S.D. = 11.22
Note 2, 84 cements
*Coef./s.d. ratio less than 1.0.

TABLE 11–4. *Calculated contributions of independent variables to the durability factor of concretes having a nominal 5½ bags cement per cubic yard and a water cement ratio of 0.635 (ODUR)*

Independent variables	Ranges of variables, (percent)	Coefficients from eq 4 table 11–4	Calculated contributions to ODUR	Calculated range of contributions to ODUR
			Const. = +94	
Air content NAE cements	0 to 4.5	+6.830	0 to +31	31
C_3S	20 to 65	−0.5456	−11 to −35	24
C_2S	5 to 50	−0.8319	−4 to −42	38
Na_2O**	0 to 0.7	−7.094	0 to −5	5
K_2O	0 to 1.1	−19.34	0 to −21	21
MgO	0 to 5	−2.866	0 to −14	14
APF	*2500 to 5500	−0.00346	−9 to −19	10
Ba**	0 to 0.2	−37.03	0 to −7	7
Rb	0 to 0.01	−883	0 to −8	8
Pb**	0 to 0.05	−190.6	0 to −10	10
Ti	0 to 1.0	−14.72	0 to −15	15
Cu	0 to 0.05	−176.9	0 to −8	8

* cm^2/g.
** Coefficient of doubtful significance as coef./s.d. ratio was less than 2.0.

Somewhat different values may be obtained by use of other equations presented in table 11–3 for NAE cements and also by use of equations in table 11-2 for AE + NAE cements. Other tables of the estimated contributions are, for the sake of consistency, presented for the NAE cements. In all instances, an equation having potential compounds and all other independent variables having coef./s.d. ratios greater than 1.0 will be used. In subsection 7, a summary table is also presented of equations for the AE + NAE cements.

6.1.2. Durability Factor of Series A Concretes

The frequency distribution of the durability factors of concretes made with sufficient water for a 5 ± 1-in slump (ADUR) is presented in table 11–5. All but two of the 14 concretes made with the air-entraining cements had durability factors higher than those for concretes made with any of the non-air-entrained cements and 78 percent of the non-air-entrained concretes had durability factors below 30. There was an overlapping of the durability values of the NAE concretes made with the different types and a broad distribution of results.

The equations relating the durability factor of AE + NAE cements to the independent variables are presented in table 11–6. Equations 1 and 2 indicate the relationships of the air content and the saturation ratio (ASAT) respectively to the durability factor. The coefficients of both independent variables were highly significant, and in both equations there were highly significant reductions in variance. (See table 11–27).

The use of air content together with other commonly determined variables C_3S, K_2O, MgO, and APF in eq 3 resulted in a further significant reduction in variance, and the additional use of the trace elements Ba, Rb, Pb, Ti, and Cu in eq 4 resulted in a further reduction in variance, significant at the 1.0 percent level. (See table 11–27, p. 00.) C_3S and Na_2O had coef./s.d. ratios less than 1.0 when included with the other variables with the 5 ± 1-in slump concretes but greater than 1.0 in the equations in table 11–2 for the 0.635 w/c concretes.

The use of the oxides CaO and SiO_2 as independent variables (eq 5) together with other commonly determined variables, K_2O, MgO, and fineness, resulted in an S.D. value comparable with that of eq 3 where C_2S was used, and a highly significant reduction in variance was obtained. (See table 11–27.) The fineness of the cements had a coef./s.d. ratio less than 1.0 when included with the other variables in eq 5 but between 1.0 and 2.0 in eq 6. When fineness was used as an independent variable together with the trace elements and other commonly determined variables (eq 6), there was a reduction in variance significant at the 1.0-percent level although the coefficients of none of the added independent variables were, individually, highly significant.

In equations for the "odds" and "evens," eqs 4A, 4B, 6A, and 6B, there were instances where CaO, MgO, fineness, Ba, Pb, Ti, and Cu had coef./s.d. ratios less than 1.0.

The equations presented in table 11–7 indicate the independent variables associated with the durability factor for concretes having a 5 ± 1-in slump and made from NAE cements. The same independent variables had coef./s.d. ratios greater than 1.0 as in table 11–6 where the AE cements were included. The use of commonly determined variables (eqs 3 and 5) resulted in highly significant reductions in variance, and with the use of the trace elements and fineness in eqs 4 and 6, a further reduction in variance was obtained (See table 11–27.) In equations for the "odds" and "evens," eqs 4A, 4B, 6A, and 6B, there were instances where CaO, fineness, and all of the trace elements had coef./s.d. ratios less than 1.0 in one or the other of the smaller groups of cements.

The estimated contributions and ranges of the contributions to the durability factor of concretes having a 5 ± 1-in slump calculated from the coefficients of eq 4, table 11–7 are presented in table 11–8. Increased air content was associated with increased durability. Increases in C_2S, K_2O, MgO, and possibly fineness, Ti, and Cu were associated with lower durability factor values.

6.2. Weight Loss at 40 Percent Reduction of Dynamic Modulus

6.2.1. Weight Loss of Series O Concretes

The frequency distribution of weight loss of the Series O concrete specimens (OWTL) at the time of 40 percent reduction of dynamic modulus in the freezing-and-thawing test is presented in table 11–9. These concrete specimens were made using a water-cement ratio of 0.635. There was actually a slight weight gain with 11 of the concretes and

TABLE 11–5. *Frequency distribution of cements with respect to durability factor of concretes having a nominal 5½ bags cement per cubic yard and a slump of 5 ± 1 inches (ADUR)*

Type cement	Durability factor									
	0 to 10	10 to 20	20 to 30	30 to 40	40 to 50	50 to 60	60 to 70	70 to 80	80 to 90	Total
	Number of cements									
I	8	27	22	15	4	2	1			79
IA						2		3	3	8
II	12	19	26	7	1	1	1			67
IIA								1	2	3
III	3	4	6	2	3	1	1			20
IIIA									3	3
IV, V	4	7	2	2						15
Total	27	57	56	26	8	6	3	4	8	195

a loss of up to 20 to 22 percent with other concretes.

The specimens which showed a weight gain were all specimens which failed very rapidly in the freezing-and-thawing test. One-day soaking in water at 40 °F is not sufficient to saturate the specimens, as is shown below by the saturation ratios. Thus all the specimens showed weight gain in the first few cycles of freezing and thawing as the process of freezing in water forced water into unfilled pores of the concrete. Then weight losses occurred as the surface sloughed off with continued freezing-and-thawing cycles. The only specimens which showed a weight gain, consequently, were those that failed in the first few cycles while they were still taking up water and before sloughing had started.

The concretes made with the AE cements had weight-loss values above the mean for all cements. There was an overlapping of the values of the different types of cements.

The equations for AE and NAE cements relating weight loss of the concrete specimens at the time of 40 percent reduction of dynamic modulus to various independent variables are presented in table 11–10. Equation 1 indicates that increased air content was associated with increased weight loss. The use of other commonly determined variables C_3A, C_4AF, Na_2O, and K_2O (in addition to the air content) (eq 2) resulted in a significant reduction in variance. With the additional use of the trace elements Rb, Pb, Ti, and Zr (eq 3) a further reduction in variance significant at the 1.0 percent level was attained. (See table 11–27.) In equations 3A and 3B calculated for the "odds" and "evens" in the array of cements, Rb, Ti, and Zr had coef./s.d. ratios less than 1.0 in one or the other of the smaller groups.

The use of Al_2O_3, Fe_2O_3, SO_3 and Al_2O_3/SO_3 (eq 4) instead of C_3A and C_4AF as in eq 2, together with Na_2O and K_2O, the other commonly determined independent variables, also resulted in a significant reduction in S.D. value. (See table 11–27.) By using the trace elements Rb, Pb, Ti, Zr, and Cr in eq 5, a further significant reduction in variance was obtained. Each of these trace elements, as well as Al_2O_3, SO_3, and the Al_2O_3/SO ratio had coef./s.d. ratios less than 1.0 in one or the other of the equations for the "odds" and "evens" (eqs 5A and 5B).

Table 11–11 shows a series of equations for the weight loss at the time of 40 percent reduction of dynamic modulus of NAE cements. As indicated in eq 1, the coef./s.d. ratio of the air content was less than 1.0. When used with other commonly determined independent variables (eqs 2 and 4) the coef./s.d. ratio was greater than 3.0. The use of the commonly determined variables (eqs 2 and 4) resulted in highly significant reductions in variance. The additional use of trace elements Rb, Pb, Ti, and Zr (eq 3), or these together with Cr (eq 5) resulted in reductions in variance significant at the 1.0 percent level (See table 11–27). In eqs 3A, 3B, 5A, and 5B calculated for the "odds" and "evens," Rb, Zr, and Cr as well as Al_2O_3, SO_3, and Al_2O_3/SO_3 had coef./s.d. ratios less than 1.0 in one or the other or both of the equations calculated for the smaller groups.

Estimated contributions and ranges of contributions to the percentage weight loss of concretes made with NAE cements at the time of 40 percent reduction of dynamic modulus as calculated from the coefficients of eq 3, table 11–11, are presented in table 11–12. Increases in air content, C_3A, and C_4AF were associated with an increase in the weight loss. Increases in K_2O and possibly Na_2O, Rb, Pb, and Ti were associated with a decrease in the weight loss.

6.2.2. Weight Loss of Series A Concretes

The frequency distribution of the weight loss of Series A concrete specimens (AWTL) at the time of 40 percent reduction of dynamic modulus in the freezing-and-thawing tests is presented in table 11–13. These concretes were made with sufficient water to produce a 5 ± 1-in slump. The specimens made with the air-entraining cements all had weight-loss values above the average for all specimens, but there was some overlapping with the concretes made with NAE cements. There was an overlapping of the groups of values

TABLE 11–6. *Coefficients for equations for AE + NAE cements relating the freeze-thaw durability factor for concretes of nominal 5 ½ bags cement per cubic yard and a slump of 5 ± 1 inch to various independent variables*

Eq. No.	Note		Const.	Air content	C_2S	CaO	SiO_2	K_2O	MgO	APF	Ba	Rb	Pb	Ti	Cu	ASAT	S.D.
1	1	ADUR	= +12.18	+7.217													11.87
		s.d.	= (1.29)	(0.473)													
2	1	ADUR	= +98.06													−119.7	12.86
		s.d.	= (5.54)													(9.1)	
3	1	ADUR	= +44.21	+7.760	−0.5768			−17.35	−1.528	−0.00203							10.57
		s.d.	= (8.44)	(0.437)	(0.1215)			(4.02)	(0.739)	(0.00170)							
4	1	ADUR	= +52.38	+7.820	−0.4679			−15.93	−2.378	−0.00297	−47.94	−895.2	−204.1	−12.55	−232.0		10.08
		s.d.	= (8.40)	(0.424)	(0.1185)			(4.37)	(0.735)	(0.00164)	(23.53)	(461.1)	(128.0)	(6.77)	(92.2)		
4A	2	ADUR (odd)	= +52.68	+8.582	−0.4051			−23.79	−2.971	*−0.00136	−112.37	−861.1	−215.6	−17.41	−320.5		10.47
		s.d.	= (12.69)	(0.686)	(0.1745)			(6.02)	(1.106)	(0.00254)	(36.40)	(664.5)	(189.5)	(8.44)	(130.0)		
4B	3	ADUR (even)	= +51.24	+7.519	−0.4749			−10.95	−1.935	−0.00390	*−1.71	−763.4	*−165.2	−16.03	*−125.5		9.63
		s.d.	= (12.19)	(0.545)	(0.1752)			(7.05)	(1.016)	(0.00236)	(33.47)	(657.0)	(180.3)	(13.79)	(138.4)		
5	1	ADUR	= −36.07	+7.735		+1.945	−3.040	−18.29	−0.992								10.55
		s.d.	= (67.29)	(0.435)		(0.973)	(0.700)	(4.33)	(0.977)								
6	1	ADUR	= +16.01	+7.809		+1.284	−2.727	−17.51	−2.160	−0.00230	−40.55	−988.6	−184.9	−13.18	−232.4		10.09
		s.d.	= (66.84)	(0.425)		(0.956)	(0.732)	(4.75)	(0.981)	(0.00159)	(23.77)	(462.3)	(128.7)	(6.77)	(93.6)		
6A	2	ADUR (odd)	= −125.3	+8.597		+3.026	−1.616	−22.03	*−1.493	*+0.00019	−112.55	−844.5	−208.7	−17.48	−281.3		10.44
		s.d.	= (113.7)	(0.683)		(1.540)	(1.231)	(6.56)	(1.531)	(0.00265)	(39.00)	(672.2)	(189.2)	(8.33)	(136.1)		
6B	3	ADUR (even)	= +66.65	+7.427		*+0.504	−2.823	−12.86	−2.233	−0.00292	*−5.304	−815.6	*−121.2	*−13.74	*−122.8		9.61
		s.d.	= (87.75)	(0.542)		(1.302)	(0.968	(7.36)	(1.378)	(0.00208)	(33.57)	(654.4)	(181.7)	(13.78)	(139.61)		

Note 1, 175 cements, Avg. = 26.33, S.D. = 18.14
Note 2, 88 cements
Note 3, 87 cements
*Coef./s.d. ratio less than 1.0.

TABLE 11–7. *Coefficients for equations for NAE cements relating the freeze-thaw durability factor for concretes of nominal 5 ½ bags cement per cubic yard and a slump of 5 ± 1 inch to various independent variables (ADUR)*

Eq. No.	Note		Const.	Air content	C_2S	CaO	SiO_2	K_2O	MgO	APF	Ba	Rb	Pb	Ti	Cu	ASAT	S.D.
1	1	ADUR	= +16.73	+3.886													11.17
		s.d.	= (1.76)	(0.996)													
2	1	ADUR	= +60.02													−60.56	10.47
		s.d.	= (5.98)													(9.61)	
3	1	ADUR	= +46.77	+5.208	−0.5048			−15.32	−1.689	−0.00245							10.03
		s.d.	= (8.17)	(0.935)	(0.1171)			(3.98)	(0.717)	(0.00167)							
4	1	ADUR	= +53.97	+6.539	−0.4106			−16.03	−2.470	−0.00337	−43.60	−675.9	−184.4	−13.56	−281.1		9.65
		s.d.	= (8.19)	(0.957)	(0.1153)			(4.35)	(0.723)	(0.00163)	(23.05)	(451.1)	(123.5)	(6.77)	(90.2)		
4A	2	ADUR (odd)	= +57.17	+6.593	−0.3187			−21.03	−1.555	−0.00520	*−15.69	−812.1	*−194.5	*−10.25	−250.7		10.78
		s.d.	= (14.04)	(1.448)	(0.1870)			(6.61)	(1.187)	(0.00255)	(50.94)	(689.4)	(195.1)	(12.21)	(139.7)		
4B	2	ADUR (even)	= +48.72	+6.382	−0.4826			−10.12	−3.332	*−0.00130	−59.12	*−595.4	*−152.8	−16.82	−139.8		8.62
		s.d.	= (10.44)	(1.321)	(0.1643)			(6.25)	(0.933)	(0.00221)	(25.49)	(624.4)	(163.5)	(8.34)	(121.1)		
5	1	ADUR	= −39.75	+5.190		+1.897	−2.614	−15.65	−1.098								9.98
		s.d.	= (65.55)	(0.935)		(0.942)	(0.686)	(4.29)	(0.952)								
6	1	ADUR	= +27.67	+6.606		+1.120	−2.589	−17.94	−2.322	−0.00298	−37.00	−769.6	−165.3	−14.38	−218.4		9.61
		s.d.	= (66.39)	(0.962)		(0.941)	(0.717)	(4.72)	(0.976)	(0.00158)	(23.11)	(451.5)	(123.4)	(6.73)	(91.5)		
6A	2	ADUR (odd)	= +117.33	+7.023		*−0.056	−2.822	−25.12	−2.216	−0.00521	*−11.31	−924.4	*−161.2	*−10.43	−300.5		10.64
		s.d.	= (103.26)	(1.463)		(1.505)	(1.169)	(7.02)	(1.548)	(0.00244)	(51.53)	(683.5)	(192.7)	(12.18)	(144.9)		
6B	2	ADUR (even)	= −108.34	+6.203		+2.830	−2.051	−7.58	−2.024	*+0.00013	−55.00	−631.5	−165.8	−16.80	*−115.3		8.60
		s.d.	= (93.54)	(1.323)		(1.320)	(0.951)	(6.69)	(1.335)	(0.00218)	(25.56)	(624.9)	(162.4)	(8.29)	(122.2)		

Note 1, 164 cements, Avg. = 22.70, S.D. = 11.64
Note 2, 82 cements
*Coef./s.d. ratio less than 1.0.

TABLE 11–8. *Calculated contributions of independent variables to the durability factor of concretes having a nominal 5½ bags cement per cubic yard and a slump of 5 ± 1 inch (ADUR)*

Independent variables	Range of variable (percent)	Coefficients from eq 4 table 11–7	Calculated Contributions to ADUR	Calculated range of contribution to ADUR
			Const. = +54	
Air content				
NAE cements	0 to 5.0	+6.539	0 to +33	33
C_2S	5 to 50	−0.4106	−2 to −21	19
K_2O	0 to 1.1	−16.03	0 to −18	18
MgO	0 to 5.0	−2.47	0 to −12	12
APF	*2500 to 5500	−0.00337	−8 to −19	11
Ba**	0 to 0.2	−43.6	0 to −9	9
Rb**	0 to 0.01	−675.9	0 to −7	7
Pb**	0 to 0.05	−184.4	0 to −9	9
Ti	0 to 1.0	−13.56	0 to −14	14
Cu	0 to 0.05	−218.1	0 to −11	11

* Cm^2/g.
** Coefficient of doubtful significance as coef./s.d. ratio was less than 2.0.

for the different types of NAE cements. As indicated in table 11–13, a few cements showed the slight weight gain characteristic of specimens which failed in the first few cycles.

The series of equations presented in table 11–14 indicates the association of various independent variables to the percentage weight loss (AWTL) at the time of 40 percent reduction in dynamic modulus of specimens made of Series A concretes. Equation 1 indicates that an increase in the water/cement ratio is associated at the 5.0 percent significance level with a decrease in the weight loss. (See table 11–27.) Equation 2 indicates the relationship of the air content of the concrete to the weight loss. The reduction in variance is greater than for eq 1. The additional use of other commonly determined variables C_3A, C_4AF, Na_2O, and K_2O in eq 3, or Al_2O_3, Fe_2O_3, Na_2O, and K_2O in eq 5, caused a reduction in variance, significant at the 1.0 percent level. The additional use of the

TABLE 11–9. *Frequency distribution of cements with respect to percentage weight loss of concrete specimens at the time of 40 percent loss of dynamic modulus in the freeze-thaw test. The specimens were made of concretes having a nominal 5½ bags cement per cubic yard and a water-cement ratio of 0.635 (OWTL)*

Type cement	Percentage weight loss												
	−2 to 0	0 to 2	2 to 4	4 to 6	6 to 8	8 to 10	10 to 12	12 to 14	14 to 16	16 to 18	18 to 20	20 to 22	Total
	Number of cements												
I	5	17	12	16	8	12	6	4		2			82
IA						1		3	3	1			8
II	2	13	5	14	9	12	7	5				1	68
IIA									2	1			3
III	3	3	3	3	2	3	1	1			1		20
IIIA							2		1				3
IV, V	1	4	1	2	3	3	1						15
Total	11	37	21	35	22	31	17	13	6	4	1	1	199

Table 11–10. *Coefficients for equations for AE + NAE cements relating the percentage weight loss in the freeze-thaw durability test at the time of 40 percent reduction of dynamic modulus of concretes of nominal 5 ½ bags cement per cubic yard and a water cement ratio of 0.635 to various independent variables (OWTL)*

Eq. No.	Note		Const.	Air content	C_3A	C_4AF	Al_2O_3	Fe_2O_3	Na_2O	K_2O	SO_3	$\frac{Al_2O_3}{SO_3}$	Rb	Pb	Ti	Zr	Cr	S.D.
1	1	OWTL	= +4.191	+1.042														3.968
		s.d.	= (0.452)	(0.163)														
2	1	OWTL	= −1.645	+1.437	+0.4044	+0.6991			−3.079	−9.739								3.352
		s.d.	= (1.914)	(0.147)	(0.1066)	(0.1372)			(1.545)	(1.265)								
3	1	OWTL	= −1.150	+1.422	+0.4112	+0.7526			−3.709	−8.435			−315.5	−85.95	−6.349	+11.22		3.177
		s.d.	= (1.878)	(0.142)	(0.1025)	(0.1314)			(1.490)	(1.336)			(143.6)	(40.34)	(2.059)	(6.15)		
3A	2	OWTL (odd)	= −4.747	+1.232	+0.4278	+1.0863			−3.109	−8.511			*−163.1	−366.2	*+2.306	+11.08		2.880
		s.d.	= (2.379)	(0.185)	(0.1318)	(0.1727)			(1.692)	(1.768)			(194.7)	(100.6)	(3.119)	(6.03)		
3B	2	OWTL (even)	= +0.917	+1.656	+0.4277	+0.5552			−4.933	−9.522			−284.7	−57.45	−7.370	*+13.28		3.339
		s.d.	= (3.063)	(0.215)	(0.1605)	(0.2096)			(2.724)	(2.024)			(216.4)	(47.60)	(3.051)	(17.71)		
4	1	OWTL	= +6.643	+1.438			+2.745	+1.475	−3.516	−9.829	−4.498	−3.013						3.345
		s.d.	= (5.522)	(0.148)			(1.084)	(0.347)	(1.567)	(1.283)	(2.815)	(1.906)						
5	1	OWTL	= +7.358	+1.430			+2.548	+1.607	−4.109	−8.646	−4.419	−2.584	−286.7	−77.89	−6.131	+10.44	−63.04	3.168
		s.d.	= (5.352)	(0.143)			(1.031)	(0.331)	(1.509)	(1.375)	(2.681)	(1.817)	(146.0)	(40.84)	(2.122)	(6.15)	(58.49)	
5A	2	OWTL (odd)	= −5.301	+1.229			*−0.646	+2.632	−2.887	−8.675	*+0.636	*+0.868	*−94.08	−374.5	*−2.217	+10.05	−109.44	2.890
		s.d.	= (9.465)	(0.189)			(1.811)	(0.438)	(1.708)	(1.804)	(4.848)	(3.318)	(201.58)	(101.4)	(3.374)	(6.10)	(71.94)	
5B	2	OWTL (even)	= +13.84	+1.702			+3.555	+1.000	−6.613	−10.043	−6.839	−4.156	*−204.0	*−45.08	−7.161	*+11.28	*−81.83	3.305
		s.d.	= (7.04)	(0.214)			(1.384)	(0.524)	(2.819)	(2.150)	(3.437)	(2.333)	(220.6)	(48.65)	(3.124)	(17.62)	(96.80)	

Note 1, 180 cements, Avg. = 6.375, S.D. = 4.386 Note 2, 90 cements *Coef./s.d. ratio less than 1.0.

Table 11–11. *Coefficients for equations for NAE cements relating the percentage weight loss in the freeze-thaw durability test at the time of 40 percent reduction of dynamic modulus of concretes of nominal 5 ½ bags cement per cubic yard and a water cement ratio of 0.635 to various independent variables (OWTL)*

Eq. No.	Note		Const.	Air content	C_3A	C_4AF	Al_2O_3	Fe_2O_3	Na_2O	K_2O	SO_3	$\frac{Al_2O_3}{SO_3}$	Rb	Pb	Ti	Zr	Cr	S.D.
1	1	OWTL	= +5.202	*+0.394														4.041
		s.d.	= (0.755)	(0.415)														
2	1	OWTL	= −1.870	+1.470	+0.4285	+0.7113			−3.185	−10.03								3.426
		s.d.	= (2.078)	(0.383)	(0.1118)	(0.1433)			(1.621)	(1.35)								
3	1	OWTL	= −2.112	+1.881	+0.4462	+0.8014			−4.168	−8.96			−344.4	−88.71	−7.28	+12.34		3.216
		s.d.	= (2.027)	(0.369)	(0.1066)	(0.1368)			(1.556)	(1.40)			(149.0)	(41.03)	(2.16)	(6.29)		
3A	2	OWTL (odd)	= −2.018	+2.109	+0.3147	+0.7513			−3.705	−7.33			*−136.4	−253.2	−5.98	+14.35		3.199
		s.d.	= (2.641)	(0.504)	(0.1476)	(0.1765)			(1.982)	(1.96)			(210.4)	(152.2)	(3.60)	(6.51)		
3B	2	OWTL (even)	= −3.486	+1.791	+0.5752	+0.9155			−4.477	−10.48			−471.6	−66.58	−5.40	*−18.38		3.292
		s.d.	= (3.350)	(0.577)	(0.1625)	(0.2307)			(2.749)	(2.14)			(237.2)	(45.43)	(3.59)	(40.16)		
4	1	OWTL	= +6.744	+1.541			+2.919	+1.482	+3.701	−10.21	−4.718	−3.214						3.419
		s.d.	= (5.756)	(0.385)			(1.140)	(0.363)	(1.653)	(1.37)	(2.964)	(1.993)						
5	1	OWTL	= +7.724	+1.968			+2.914	+1.696	−4.768	−9.33	−5.117	−3.089	−314.5	−81.15	−7.02	+11.75	−68.12	3.203
		s.d.	= (5.549)	(0.370)			(0.072)	(0.344)	(1.582)	(1.45)	(2.795)	(1.879)	(151.7)	(41.44)	(2.22)	(6.28)	(61.36)	
5A	2	OWTL (odd)	= −11.901	+2.140			*−1.455	+1.701	−3.341	−7.20	*+5.501	+4.224	*−76.7	−275.72	−5.88	+13.07	*−72.46	3.217
		s.d.	= (12.213)	(0.514)			(2.294)	(0.453)	(2.017)	(2.012)	(6.220)	(4.189)	(215.8)	(155.01)	(3.77)	(6.65)	(87.17)	
5B	2	OWTL (even)	= +12.24	+1.994			+4.641	+1.930	−6.601	−10.92	−8.506	−5.506	−373.2	−59.84	−3.92	−42.41	*−61.60	3.221
		s.d.	= (7.05)	(0.572)			(1.360)	(0.580)	(2.822)	(2.30)	(3.435)	(2.332)	(246.6)	(45.84)	(3.70)	(41.35)	(91.61)	

Note 1, 168 cements, Avg. = 5.855, S.D. = 4.039 Note 2, 84 cements *Coef./s.d. ratio less than 1.0.

TABLE 11–12. *Calculated contributions of independent variables to the percentage weight loss in the freeze-thaw durability test at the time of 40 percent reduction of dynamic modulus of concretes of nominal 5 ½ bags cement per cubic yard and a water cement ratio of 0.635 (OWTL)*

Independent variables	Range of variable (percent)	Coefficients from eq. 3 table 11–11	Calculated contributions to OWTL	Calculated range of contribution to OWTL
			Const. = −2.1	
Air content NAE cements	0 to 4.5	+1.881	0 to +8.5	8.5
C_3A	1 to 15	+0.4462	+0.4 to 6.7	6.3
C_4AF	1 to 16	+0.8041	+0.8 to +12.9	12.1
Na_2O	0 to 0.7	−4.168	0 to −2.9	2.9
K_2O	0 to 1.1	−8.96	0 to −9.9	9.9
Rb	0 to 0.01	−344.4	0 to −3.4	3.4
Pb	0 to 0.05	−88.71	0 to −4.5	4.5
Ti	0 to 1.0	−7.28	0 to −7.3	7.3
Zr**	0 to 0.5	+12.34	0 to +6.2	6.2

** Coefficient of doubtful significance as coef./s.d. ratio was less than 2.0.

trace elements, Mn, Rb, Pb, and Ti (eqs 4 and 6) resulted in a further reduction in variance (see table 11–27) although the coefficients for the individual trace elements were not highly significant. In equations calculated for the "odds" and "evens," eqs 4A, 4B, 6A, and 6B, the coef./s.d. ratios for Fe_2O_3, Na_2O, Pb, and Ti were less than 1.0 in one or the other of the equations calculated for the smaller groups of cements.

An analogous series of equations for the NAE cements is presented in table 11–15. The coef./s.d. ratios of w/c and air content (eqs 1 and 2) were both less than 1.0. When these were used with other commonly determined variables (eqs 3 and 5), the coefficient for air content was probably significant, and the reduction in variance as a result of the added variables was highly significant. The additional use of four trace elements (eqs 4 and 6) caused a further reduction in vari-

TABLE 11–13. *Frequency distribution of cements with respect to percentage weight loss of concrete specimens at the time of 40 percent loss of dynamic modulus in the freeze-thaw test. The specimens were made of concretes having a nominal 5 ½ bags cement per cubic yard and a slump of 5 ± 1 inches (AWTL)*

Type cement	Percentage weight loss												
	−2 to 0	0 to 2	2 to 4	4 to 6	6 to 8	8 to 10	10 to 12	12 to 14	14 to 16	16 to 18	18 to 20	20 or more	Total
	Number of cements												
I	4	16	11	9	11	14	9	2	2	-	-	1	79
IA	-	-	-	-	-	1	-	3	3	1	-	-	8
II	3	10	9	10	11	11	5	6	1	-	-	1	67
IIA	-	-	-	-	-	-	1	2	-	-	-	-	3
III	2	1	5	2	3	2	3	1	-	-	1	-	20
IIIA	-	-	-	-	-	-	2	1	-	-	-	-	3
IV, V	1	5	1	2	2	2	1	1	-	-	-	-	15
Total	10	32	26	23	27	30	21	16	6	1	1	2	195

TABLE 11–14. *Coefficients for equations for AE + NAE cements relating the percentage weight-loss in the freeze-thaw durability test at the time of 40 percent reduction of dynamic modulus of concretes of nominal 5 ½ bags cement per cubic yard and a slump of 5 ± 1 inch to various independent variables (AWTL)*

Eq. No.	Note		Const.	Air content	C_3A	C_4AF	Al_2O_3	Fe_2O_3	Na_2O	K_2O	Mn	Rb	Pb	Ti	w/c	S.D.
1	1	AWTL	= +26.13												−30.69	4.104
		s.d.	= (8.07)												(12.66)	
2	1	AWTL	= +5.366	+0.5980												3.982
		s.d.	= (0.420)	(0.1447)												
3	1	AWTL	= +0.997	+0.8991	+0.4751	+0.5074			−1.966	−10.27						3.418
		s.d.	= (1.969)	(0.1321)	(0.1092)	(0.1415)			(1.584)	(1.30)						
4	1	AWTL	= +1.157	+0.9020	+0.5275	+0.6059			−2.527	−9.70	−4.903	−329.2	−52.45	−4.379		3.287
		s.d.	= (1.956)	(0.1297)	(0.1081)	(0.1396)			(1.538)	(1.39)	(2.119)	(150.1)	(41.80)	(2.145)		
4A	2	AWTL (odd)	= −2.940	+0.9092	+0.5772	+0.9466			−2.652	−10.84	−3.976	−279.1	*−46.87	*+0.469		3.387
		s.d.	= (3.045)	(0.1677)	(0.1691)	(0.2112)			(2.386)	(2.10)	(2.713)	(225.0)	(62.38)	(3.332)		
4B	2	AWTL (even)	= +4.110	+0.8862	+0.4539	+0.3227			*−1.865	−7.55	−7.518	−434.8	−60.77	−6.988		3.101
		s.d.	= (2.513)	(0.2136)	(0.1368)	(0.1846)			(2.008)	(1.87)	(3.479)	(199.1)	(55.10)	(2.823)		
5	1	AWTL	= +0.948	+0.8984			+1.264	+0.7496	−1.975	−10.28						3.417
		s.d.	= (1.972)	(0.1320)			(0.289)	(0.3571)	(1.583)	(1.30)						
6	1	AWTL	= +1.102	+0.9012			+1.403	+0.9630	−2.537	−9.70	−4.900	329.7	−52.76	−4.395		3.285
		s.d.	= (1.957)	(0.1295)			(0.286)	(0.3483)	(1.537)	(1.39)	(2.117)	(150.0)	(41.76)	(2.144)		
6A	2	AWTL (odd)	= −3.046	+0.9077			+1.545	+1.9236	−2.665	−10.89	−3.995	−279.6	*−46.84	*+0.421		3.380
		s.d.	= (3.039)	(0.1673)			(0.448)	(0.5286)	(2.381)	(2.10)	(2.706)	(224.5)	(62.23)	(3.324)		
6B	2	AWTL (even)	= +4.101	+0.8859			+1.202	*+0.2155	*−1.863	−7.53	−7.507	−435.8	−61.07	−6.986		3.101
		s.d.	= (2.518)	(0.2137)			(0.362)	(0.4634)	(2.008)	(1.87)	(3.478)	(199.2)	(55.09)	(2.823)		

Note 1, 176 cements, Avg. = 6.582, S.D. = 4.161
Note 2, 88 cements
*Coef./s.d. ratio less than 1.0.

TABLE 11–15. *Coefficients for equations for NAE cements relating the percentage weight loss in the freeze-thaw durability test at the time of 40 percent reduction of dynamic modulus of concretes of nominal 5 ½ bags cement per cubic yard and a slump of 5 ± 1 inch to various independent variables (AWTL)*

Eq. No.	Note		Const.	Air content	C_3A	C_4AF	Al_2O_3	Fe_2O_3	Na_2O	K_2O	Mn	Rb	Pb	Ti	w/c	S.D.
1	1	ATWL =	−0.651												* +10.69	4.045
		s.d. =	(10.723)												(16.72)	
2	1	AWTL =	+6.054	* +0.0954												4.049
		s.d. =	(0.641)	(0.3616)												
3	1	AWTL =	+0.740	+0.9435	+0.4990	+0.5161			−2.018	−10.52						3.489
		s.d. =	(2.123)	(0.3355)	(0.1150)	(0.1475)			(1.658)	(1.40)						
4	1	AWTL =	+0.409	+1.2442	+0.5875	+0.6593			−2.931	−10.51	−6.012	−340.8	−54.97	−5.534		3.317
		s.d. =	(2.081)	(0.3298)	(0.1134)	(0.1449)			(1.597)	(1.47)	(2.238)	(154.7)	(42.58)	(2.254)		
4A	2	AWTL (odd) =	+0.678	+1.541	+0.5822	+0.6751			−4.943	−12.13	−3.510	−362.9	* −48.78	−4.690		3.462
		s.d. =	(3.146)	(0.4797)	(0.1817)	(0.2126)			(2.556)	(2.15)	(2.955)	(223.2)	(63.29)	(3.661)		
4B	2	AWTL (even) =	+1.284	+0.8012	+0.5521	+0.5766			* −1.299	−8.08	−13.784	−244.9	−67.14	−5.511		3.149
		s.d. =	(2.881)	(0.4638)	(0.1461)	(0.2078)			(2.051)	(2.08)	(3.871)	(221.1)	(58.64)	(2.878)		
5	1	AWTL =	+0.692	+0.9419			+1.327	+0.7356	−2.028	−10.53						3.487
		s.d. =	(2.125)	(0.3352)			(0.305)	(0.3703)	(1.658)	(1.40)						
6	1	AWTL =	+0.355	+1.2430			+1.562	+1.0238	−2.944	−10.52	−6.009	−341.2	−55.31	−5.552		3.315
		s.d. =	(2.081)	(0.3294)			(0.300)	(0.3583)	(1.596)	(1.47)	(2.236)	(154.6)	(42.54)	(2.253)		
6A	2	AWTL (odd) =	+0.570	+1.5404			+1.560	+1.0858	−4.987	−12.17	−3.532	−363.6	* −48.78	−4.716		3.454
		s.d. =	(3.135)	(0.4783)			(0.481)	(0.5104)	(2.552)	(2.15)	(2.947)	(227.7)	(63.15)	(3.652)		
6B	2	AWTL (even) =	+1.278	+0.8009			+1.461	+0.8255	* −1.230	−8.07	−13.788	−245.5	−67.77	−5.526		3.150
		s.d. =	(2.891)	(0.4639)			(0.387)	(0.5255)	(2.052)	(2.08)	(3.873)	(221.2)	(58.65)	(2.881)		

Note 1, 164 cements, Avg. = 6.201, S.D. = 4.038
Note 2, 82 cements
*Coef./s.d. ratio less than 1.0.

TABLE 11–16. *Calculated contributions of independent variables to the percentage weight loss in the freeze-thaw durability test at the time of 40 percent reduction of dynamic modulus of concretes of nominal 5 ½ bags cement per cubic yard and a slump of 5 ± 1 inch. (AWTL)*

Independent variables	Range of variable (percent)	Coefficients from eq 4 table 11–15	Calculated contributions to AWTL	Calculated ranges of contribution to AWTL
			Const. = +0.4	
Air content				
NAE cements	0 to 5.0	+1.244	0 to +6.2	6.2
C_3A	1 to 15	+0.5875	+0.6 to +8.8	8.2
C_4AF	1 to 16	+0.6593	0 to +4.6	4.6
Na_2O**	0 to 0.7	−2.931	0 to −3.2	3.2
K_2O	0 to 1.1	−10.51	0 to −10.5	10.5
Mn	0 to 1.0	−6.012	0 to −6.0	6.0
Rb	0 to 0.01	−340.8	0 to −3.4	3.4
Pb**	0 to 0.05	−54.97	0 to −2.7	2.7
Ti	0 to 1.0	−5.534	0 to −5.5	5.5

** Coefficient of doubtful significance as coef./s.d. ratio was less than 2.0

ance, significant at the 1.0-percent level. (See table 11–27.) The coef./s.d. ratio of air content in eqs 4 and 6 was greater than 3.0 indicating that when used with other independent variables in an equation, the coefficient for air content of concretes made of NAE cements may be highly significant. In eqs 4A, 4B, 6A, and 6B, there were instances where Na_2O and Pb had coef./s.d. ratios less than 1.0 in one or the other of the equations for the smaller groups of cement.

The estimated contributions and range of contributions to the percentage weight loss (AWTL) in the freezing-and-thawing tests at the time of 40 percent reduction of dynamic modulus of the concretes of 5 ± 1-in slump, as calculated from the coefficients of eq 4, table 11–15, are presented in table 11–16. Tables 11–15 and 11–16 show that increases in air content, C_3A, and C_4AF were associated with increase in AWTL. Increases in K_2O, and probably Mn, Rb, and Ti were associated with decrease in AWTL. The coefficients for Na_2O and Pb were of doubtful significance.

6.3. Saturation Ratio

6.3.1. Saturation Ratio of Series O Concretes

As previously indicated in subsection 3.3, the concrete specimens, moist-cured for 14 days, then dried in laboratory air for 4 weeks, were placed in water at 40 °F for 24 hours prior to the start of the freezing-and-thawing tests. Determinations were made of the air content of the freshly-mixed concrete, the loss of weight as a result of drying, and the weight gain after the 24 hours in water. The ratio of this weight gain to the possible weight gain if completely saturated, i.e., the volume of water lost in drying plus the volume of air, was calculated and is here termed the saturation ratio.

The frequency distribution of the saturation ratios is presented in table 11–17 for Series O concretes. The values for the ratio (OSAT) ranged from less than 0.3 to more than 0.8. All of the concretes made with the AE cements (Types IA, IIA, and IIIA) had very low ratios, and the values for the concretes made with the different types of NAE cements overlapped.

Selected equations presented in table 11–18 indicate the relationship of various independent variables to the saturation ratio (OSAT) for the AE + NAE cements. As indicated in eqs 1 and 2, the ratio is significantly related to the air content (OAIR) of the concretes. A smaller S.D. value was obtained in eq 2 which used the square root of the air content as an independent variable in place of the air content as in eq 1. The additional use of C_2S and C_4AF in eq 3 resulted in a significant reduction in variance. (See table 11–27.) The reduction in variance resulting from also using MgO and Loss in eq 4 was significant at the 1.0 percent level. Comparing eqs 2 and 4 indicated an overall reduction in variance significant at the 1.0 percent level. With the added trace elements Cu, Mn, P, and Rb in addition to commonly determined variables in eq 5 there was a reduction in variance significant at the 1.0 percent level. (See table 11–27.)

TABLE 11–17. *Frequency distribution of cements with respect to the ratio of the volume water absorbed when placed in water for 24 hours divided by the volume water lost after 28 days drying in laboratory air, plus the volume of air in the concrete. The concretes were made with a water-cement ratio of 0.635 (OSAT)*

Type cement	Saturation ratio												
	0.25 to 0.30	0.30 to 0.35	0.35 to 0.40	0.40 to 0.45	0.45 to 0.50	0.50 to 0.55	0.55 to 0.60	0.60 to 0.65	0.65 to 0.70	0.70 to 0.75	0.75 to 0.80	0.80 and over	Total
	Number of cements												
I				1	11	11	29	17	11	1		1	82
IA		4	1	3									8
II				3		3	8	18	21	11	2	2	68
IIA				3									3
III					2	7	4	6		1			20
IIIA	1	1	1										3
IV, V							2	3	4	3	3		15
Total	1	5	2	10	13	21	43	44	36	16	5	3	199

TABLE 11–18. *Coefficients for equations for AE + NAE cements relating the saturation cubic yard and a water-cement ratio of 0.635*

Eq. No.	Note		Const.	OAIR	$(OAIR)^{0.5}$	C_2S	C_4AF	CaO
1	1	OSAT	= +0.6745	−0.0396				
		s.d.	= (0.0073)	(0.0026)				
2	1	OSAT	= +0.7987		−0.1522			
		s.d.	= (0.0133)		(0.0092)			
3	1	OSAT	= +0.6288		−0.1406	+0.00409	+0.00538	
		s.d.	= (0.0243)		(0.0079)	(0.00054)	(0.00173)	
4	1	OSAT	= +0.5879		−0.1430	+0.00440	+0.00574	
		s.d.	= (0.0285)		(0.0079)	(0.00055)	(0.00171)	
5	1	OSAT	= +0.5858		−0.1447	+0.00441	+0.00537	
		s.d.	= (0.0283)		(0.0077)	(0.00055)	(0.00176)	
5A	2	OSAT (odd)	= +0.6197		−0.1376	+0.00416	+0.00480	
		s.d.	= (0.0447)		(0.0115)	(0.00078)	(0.00283)	
5B	2	OSAT (even)	= +0.5628		−0.1524	+0.00455	+0.00524	
		s.d.	= (0.0381)		(0.0104)	(0.00082)	(0.00232)	
6	1	OSAT	= +1.486		−0.1434			−0.01932
		s.d.	(0.223)		(0.0079)			(0.00347)
7	1	OSAT	= +1.734		−0.1465			−0.02246
		s.d.	= (0.234)		(0.0078)			(0.00355)
7A	2	OSAT (odd)	= +1.363		−0.1394			−0.01797
		s.d.	= (0.365)		(0.0114)			(0.00563)
7B	2	OSAT (even)	= +2.126		−0.1553			−0.02711
		s.d.	= (0.318)		(0.0109)			(0.00471)

Note 1, 178 cements, Avg. = 0.5911, S.D. = 0.0963
Note 2, 89 cements
*Coef./s.d. ratio less than 1.0.

TABLE 11–19. *Coefficients for equations for NAE cements relating the saturation ratio and a water-cement ratio of 0.635 to*

Eq. No.	Note		Const.	OAIR	$(OAIR)^{0.5}$	C_2S	C_4AF	CaO
1	1	OSAT	= +0.7122	−0.0633				
		s.d.	= (0.0115)	(0.0063)				
2	1	OSAT	= +0.8175		−0.1676			
		s.d.	= (0.0209)		(0.0162)			
3	1	OSAT	= +0.6400		−0.1475	+0.00396	+0.00541	
		s.d.	= (0.0296)		(0.0140)	(0.00056)	(0.00180)	
4	1	OSAT	= +0.5983		−0.1464	+0.00426	+0.00572	
		s.d.	= (0.0342)		(0.0139)	(0.00058)	(0.00178)	
5	1	OSAT	= +0.6023		−0.1526	+0.00426	+0.00523	
		s.d.	= (0.0338)		(0.0144)	(0.00058)	(0.00184)	
5A	2	OSAT (odd)	= +0.6247		−0.1485	+0.00462	+0.00415	
		s.d.	= (0.0567)		(0.0255)	(0.00081)	(0.00302)	
5B	2	OSAT (even)	= +0.5777		−0.1567	+0.00354	+0.00723	
		s.d.	= (0.0428)		(0.0174)	(0.00085)	(0.00235)	
6	1	OSAT	= +1.411		−0.1475			−0.01801
		s.d.	= (0.231)		(0.0138)			(0.00359)
7	1	OSAT	= +1.674		−0.1552			−0.02124
		s.d.	= (0.241)		(0.0144)			(0.00365)
7A	2	OSAT (odd)	= +1.482		−0.1550			−0.02040
		s.d.	= (0.336)		(0.0243)			(0.00523)
7B	2	OSAT (even)	= +1.937		−0.1605			−0.02262
		s.d.	= (0.347)		(0.0178)			(0.00514)

Note 1, 166 cements, Avg. = 0.6070, S.D. = 0.07757
Note 2, 88 cements
*Coef./s.d. ratio less than 1.0.

ratio at the start of the freeze-thaw tests of concretes of nominal 5 ½ bags cement per
to various independent variables (OSAT)

SiO_2	Fe_2O_3	MgO	Loss	Cu	Mn	Ni	P	Rb	S.D.
----------	----------	----------	----------	----------	----------	----------	----------	----------	0.06376
----------	----------	----------	----------	----------	----------	----------	----------	----------	0.06023
----------	----------	----------	----------	----------	----------	----------	----------	----------	0.05011
----------	----------	+0.00612 (0.00319)	+0.01483 (0.00715)	----------	----------	----------	----------	----------	0.04932
----------	----------	+0.00936 (0.00324)	+0.01660 (0.00707)	+0.9163 (0.4522)	−0.0631 (0.0452)	----------	+0.0442 (0.0341)	−3.653 (1.952)	0.04792
----------	----------	*+0.00489 (0.00512)	*+0.00334 (0.01113)	+0.7838 (0.6849)	*−0.0419 (0.0440)	----------	*+0.0205 (0.0526)	−5.557 (2.657)	0.05070
----------	----------	+0.01238 (0.00435)	+0.02943 (0.00948)	+1.3715 (0.6409)	−0.0885 (0.0459)	----------	+0.0599 (0.0465)	*−1.195 (3.061)	0.04561
+0.02271 (0.00309)	+0.01239 (0.00547)	----------	----------	----------	----------	----------	----------	----------	0.04912
+0.02134 (0.00316)	+0.00946 (0.00575)	----------	----------	+0.9583 (0.4524)	−0.0529 (0.0315)	−1.354 (1.151)	+0.0453 (0.0343)	−3.163 (2.014)	0.04787
+0.02472 (0.00470)	+0.01008 (0.00898)	----------	----------	+1.0170 (0.6775)	*−0.0268 (0.0436)	*−0.616 (1.624)	*+0.0290 (0.0526)	−4.345 (2.776)	0.04997
*+0.01798 (0.00468)	*+0.00507 (0.00777)	----------	----------	+1.2872 (0.6753)	−0.0799 (0.0479)	−1.997 (1.818)	*+0.0361 (0.0477)	*−1.251 (3.175)	0.04659

at the start of freeze-thaw tests of concretes of nominal 5 ½ bags cement per cubic yard
various independent variables (OSAT)

SiO_2	Fe_2O_3	MgO	Loss	Cu	Mn	Ni	P	Rb	S.D.
----------	----------	----------	----------	----------	----------	----------	----------	----------	0.06124
----------	----------	----------	----------	----------	----------	----------	----------	----------	0.06055
----------	----------	----------	----------	----------	----------	----------	----------	----------	0.05077
----------	----------	+0.00550 (0.00330)	+0.01397 (0.00752)	----------	----------	----------	----------	----------	0.05016
----------	----------	+0.00885 (0.00332)	+0.01601 (0.00737)	+0.982 (0.473)	−0.0726 (0.0327)	----------	+0.0488 (0.0348)	−3.35 (2.05)	0.04847
----------	----------	+0.00550 (0.00496)	*+0.01043 (0.01231)	*+0.670 (0.757)	−0.0624 (0.0438)	----------	*+0.0123 (0.0555)	−4.79 (2.96)	0.05123
----------	----------	+0.02111 (0.00456)	+0.02489 (0.00938)	+1.297 (0.601)	−0.1012 (0.0512)	----------	+0.0768 (0.0456)	*−1.70 (3.07)	0.04556
+0.02242 (0.00322)	+0.01307 (0.00567)	----------	----------	----------	----------	----------	----------	----------	0.04973
+0.02092 (0.00328)	+0.00962 (0.00599)	----------	----------	+1.019 (0.471)	−0.0599 (0.0329)	*−1.162 (1.175)	+0.0502 (0.0350)	−2.78 (2.11)	0.04833
+0.02807 (0.00467)	*+0.00592 (0.00922)	----------	----------	*+0.643 (0.724)	−0.0458 (0.0423)	*+0.036 (1.792)	*+0.0244 (0.0535)	−2.85 (3.03)	0.04926
+0.01255 (0.00462)	+0.01228 (0.00782)	----------	----------	+1.522 (0.613)	−0.0796 (0.0532)	−2.170 (1.578)	+0.0598 (0.0470)	*−2.72 (3.12)	0.04633

TABLE 11–20. *Calculated contributions of independent variables to the saturation ratio at the start of the freeze-thaw tests of concretes of nominal 5 ½ bags cement per cubic yard and a water-cement ratio of 0.635 (OSAT)*

Independent variables	Range of variables (percent)	Coefficients from eq 5 table 11–19	Calculated contributions to OSAT	Calculated range of contribution to OSAT
			Const. = +0.60	
$(OAIR)^{0.5}$				
NAE cements	0 to 2.12	−0.1526	0 to −0.32	0.32
C_2S	5 to 50	+0.00426	+0.02 to +0.21	0.19
C_4AF	1 to 16	+0.00523	+0.01 to +0.08	0.07
MgO	0 to 5.0	+0.00885	0 to +0.04	0.04
Loss	0.3 to 3.3	+0.01601	0 to +0.05	0.05
Cu	0 to 0.05	+0.982	0 to +0.05	0.05
Mn	0 to 1	−0.0726	0 to −0.07	0.07
P**	0 to 0.5	+0.0488	0 to +0.02	0.02
Rb**	0 to 0.01	−3.35	0 to −0.03	0.03

** Coefficient of doubtful significance as coef./s.d. ratio less than 2.0.

Equation 6 was calculated using the oxides, CaO, SiO_2, and Fe_2O_3 as independent variables instead of the potential compounds. MgO and Loss had coef./s.d. ratios of less than 1.0 and were not included. The reduction in variance was highly significant. With the added trace elements Cu, Mn, Ni, P, and Rb (eq 7), the reduction in variance was significant at the 5.0 percent level. (See table 11–27.)

In equations calculated for the "odds" and "evens" in the array of cements, (eqs 5A, 5B, 7A, and 7B), the coef./s.d. ratios for Fe_2O_3, MgO, Loss, Mn, Ni, P, and Rb were less than 1.0 in one or the other of the pairs of equations for the smaller groups of cement.

The equations presented in table 11–19 for the relation of the various independent variables to the saturation ratio of NAE cements are very similar to, and the coefficients and coef./s.d. ratios reasonably consistent with those presented in table 11–18 where the AE cements were included. The coefficients for the air content or square root of the air content (eqs 1 and 2) were highly significant even with the NAE cements. (See table 11–27.) The additional use of C_2S and C_4AF in eq 3 resulted in a highly significant reduction in variance, but with the addition of MgO and Loss in eq 4 the reduction in variance was not significant at the 5.0 percent level. The use of trace elements Cu, Mn, P, and Rb (eq 5) caused a reduction in variance significant at the 1.0 percent level, but when these plus Ni were used with the oxides (eq 7), the added reduction in variance was significant only at the 5.0 percent level. In the equations for the "odds" and "evens" (eqs 5A, 5B, 7A, and 7B) there were instances where Fe_2O_3, Loss, Cu, Ni, P, and Rb had coef./s.d. ratios less than 1.0 in one or more of the equations for the smaller groups.

The estimated contributions and range of contributions to saturation ratio of the constant w/c concretes, as calculated from the coefficients of eq 5, table 11–19, are presented in table 11–20. Increase in air content and probably Mn were associated with a decrease in the saturation ratio, Increases in C_2S and probably C_4AF, MgO, Loss, and Cu were associated with increases of the saturation ratio.

6.3.2. Saturation Ratio of Series A Concretes

The frequency distribution of the saturation ratios of the Series A concretes is presented in table 11–21. The AE cements (Types IA, IIA, and IIIA) had low saturation ratios (0.20 to 0.45) whereas the NAE cements had ratios of 0.4 to more than 0.8. There was a broad overlapping of the ratios for the different types of NAE cements.

Equations indicating the various independent variables associated with the saturation ratio of AE + NAE cements are presented in table 11–22. The use of the square root of the air content (eq 2) resulted in a slightly lower S.D. value than when using the air content (eq 1). When the w/c required to produce the 5 ± 1-in slump concrete was included as a single additional variable in eq 3, the coefficient for w/c was not significant. In eq 4 where C_2S and C_4AF were added as independent variables, the coefficient for w/c was positive and significant at the 5.0 percent level. The use of the commonly determined variables C_2S, C_4AF, C_3A/SO_3, MgO, and Loss (eq 5) resulted in a highly significant reduction in variance. (See table 11–27.) The use of Co, Ni, P, Rb, and Zr together with commonly determined variables

TABLE 11–21. *Frequency distribution of cements with respect to the ratio of the volume water absorbed when placed in water for 24 hours divided by the volume water lost by drying for 28 days in laboratory air plus the volume of air in the concrete. The concretes were made with a slump of 5 ± 1 inches (ASAT)*

Type cement	Saturation ratio													
	0.20 to 0.25	0.25 to 0.30	0.30 to 0.35	0.35 to 0.40	0.40 to 0.45	0.45 to 0.50	0.50 to 0.55	0.55 to 0.60	0.60 to 0.65	0.65 to 0.70	0.70 to 0.75	0.75 to 0.80	0.80 and Over	Total
	Number of cements													
I					2	8	17	17	15	10	7	2	1	79
IA	1		4	1	2									8
II					2	3	5	5	16	15	15	4	2	67
IIA			1	1	1									3
III						2	4	7	5	1		1		20
IIIA		1	1	1										3
IV, V								2	5	4	2	2		15
Total	1	1	6	3	7	13	26	31	41	30	24	9	3	195

(eq 6) resulted in a highly significant reduction in variance. (See table 11–27.) The use of the oxides (eq 7), or the oxides with trace elements (eq 8) resulted in S.D. values and reduction of variance comparable with those obtained using the potential compounds in eqs 5 and 6.

In equations for the "odds" and "evens" (eqs 6A, 6B, 7A, and 7B) there were instances where C_3A/SO_3, Fe_2O_3, K_2O, MgO, Co, Rb, and Zr had coef./s.d. ratios less than 1.0 in one or the other of the pairs of equations with the smaller groups of cements.

The corresponding series of equations for NAE cements is presented in table 11–23. The results are in reasonable agreement with those presented in the previous table 11–22, where the AE cements were included.

In eq 4A and 4B the coef./s.d. ratios of Al_2O_3, Fe_2O_3, Cr, and V had coef./s.d. ratios less than 1.0 in one or the other of the equations for the smaller groups of cements, the "odds" and "evens."

The estimated contributions and range of contributions to saturation ratio of the constant slump concretes, as calculated from the coefficients of eq 6, table 11–23, are presented in table 11–24. Increases in air content, and probably C_3A/SO_3, Ni, and Rb were associated with decreases in the saturation ratio. Increases in C_2S, MgO, and probably C_4AF, Loss, and P were associated with increases of the saturation ratio.

6.4. Cycles of Freezing and Thawing

Frequency distributions of the number of cycles required to cause a 40-percent reduction of dynamic modulus of Series O and Series A concretes are given in tables 11–25 and 11–26, respectively. No analyses of these data were made because of the fact that the distribution curves for these data and those for durability factor are identical except for the air-entraining cements, and, therefore, equations, especially with NAE cements, would have shown the same relationships. For specimens which fail in 300 cycles or less, the durability factor is exactly one-fifth the number of cycles at which the 40-percent reduction in dynamic *E* is reached. All of the non-air-entrained specimens failed in 300 cycles or less, and thus the distribution curves are the same for dynamic *E* and number of cycles up to this point. (There are some discrepancies in the distributions given in tables 11–25 and 11–26 as compared to tables 11–1 and 11–5 due to the fact that the durability factors were rounded to the nearest unit and the numbers of cycles were taken to the nearest cycle. The three non-air-entrained cements shown in the 300–500 cell in table 11–26 were ones which failed at 300 cycles). Although the two distributions are different for specimens which do not fail in 300 cycles, the small number of air-entraining cements did not warrant further analysis using the number of cycles instead of the durability factor.

6.5. Autogenous Healing

After completion of the freezing-and-thawing tests, the deteriorated specimens were placed in the fog room. At various periods ranging from approximately one to approximately five years, the specimens were removed from the fog room and retested for dynamic modulus.

The periods during which the specimens were stored in the fog room after freezing-and-thawing tests were nominally 1, 2, 3, 4, and 5 years. However, due to the fact that large groups of specimens which had been removed from freezing and thawing at different times were retested for dynamic modulus at the same time, the actual amount of time in storage varied within each nominal age group.

The ranges of actual elapsed times in months are given in table 11–28. All of the specimens in the 4-year category were specimens which had been retested at 2 or 3 years, then were placed in the fog room and retested a second time at 4 years. A small number of these were retested a third time and are included with the 5-year group.

Since it appears, as is shown below, that practically all of the autogenous healing that occurred took place in the first year, and no statistical intercomparisons of data are made between years, it seems the variations in time within the nominal age groups do not affect the results.

Table 11–29 shows the averages and standard deviations of the ratios of dynamic modulus after autogenous healing to dynamic modulus at the end of the freezing-and-thawing test. Most of the specimens achieved calculated dynamic modulus values equal to or higher than the original dynamic modulus, but the moduli for these two periods could not be compared directly, because of the sloughing and consequent changes in dimensions that many of the specimens underwent during freezing-and-thawing. For the period of autogenous healing, however, the dimensions did not change. Also changes in weight during the healing period were negligible.

For the NAE cements alone, the average ratio for all five age groups was 2.32, while the average for the 42 specimens measured at one year was 2.38. Thus all the autogenous healing evidently occurred before 16 months. It seems probable that the length of time required for recovery was actually less than one year, but how much less is not known.

The ratios for the air-entrained specimens were significantly lower than those for the non-air-entrained specimens, an average of 1.34 for both 2- and 3-year storage compared to 2.32 for the non-air-entrained concretes. The air-entrained specimens had lower dynamic modulus values at the start of the freezing-and-thawing tests. However, the air-entrained specimens generally appeared to regain a smaller percentage of their original dynamic modulus during storage. The ratios of calculated dynamic modulus after storage

Table 11–22. *Coefficients for equations for AE + NAE cements relating the saturation cubic yard and a slump of 5 ± 1 inch to*

Eq. No.	Note		Const.	AAIR	$(AAIR)^{0.5}$	w/c	C_2S	C_4AF	C_3A/SO_3
1	1	ASAT	= +0.6827	−0.0429					
		s.d.	= (0.0067)	(0.0023)					
2	1	ASAT	= +0.8119		−0.1657				
		s.d.	= (0.0105)		(0.0074)				
3	1	ASAT	= +1.0550		−0.1774	−0.3576			
		s.d.	= (0.1814)		(0.0114)	(0.2664)			
4	1	ASAT	= +0.2505		−0.1415	+0.5867	+0.00443	+0.00464	
		s.d.	= (0.1726)		(0.0103)	(0.2391)	(0.00049)	(0.00164)	
5	1	ASAT	= +0.2258		−0.1441	+0.6212	+0.00448	+0.00358	−0.00515
		s.d.	= (0.1647)		(0.0100)	(0.2317)	(0.00050)	(0.00174)	(0.00254)
6	1	ASAT	= +0.2441		−0.1456	+0.5880	+0.00468	+0.00408	−0.00461
		s.d.	= (0.1583)		(0.0096)	(0.2229)	(0.00048)	(0.00169)	(0.00247)
6A	2	ASAT (odd)	= +0.3459		−0.1510	+0.4931	+0.00435	+0.00440	−0.00591
		s.d.	= (0.2752)		(0.0173)	(0.3880)	(0.00066)	(0.00251)	(0.00391)
6B	3	ASAT (even)	= +0.1735		−0.1429	+0.6140	+0.00495	+0.00419	*−0.00216
		s.d.	= (0.1913)		(0.0116)	(0.2676)	(0.00074)	(0.00249)	(0.00329)
7	1	ASAT	= +1.419		−0.1387	+0.6888			
		s.d.	= (0.302)		(0.0103)	(0.2377)			
8	1	ASAT	= +1.474		−0.1413	+0.6508			
		s.d.	= (0.293)		(0.0100)	(0.2303)			
8A	2	ASAT (odd)	= +1.285		−0.1502	+0.4515			
		s.d.	= (0.504)		(0.0184)	(0.4103)			
8B	3	ASAT (even)	= +1.844		−0.1416	+0.6703			
		s.d.	= (0.389)		(0.0126)	(0.2845)			

Note 1, 177 cements, Avg. = 0.5961, S.D. = 0.1097
Note 2, 89 cements
Note 3, 88 cements
*Coef./s.d. ratio less than 1.0.

Table 11–23. *Coefficients for equations for NAE cements relating the saturation ratio and a slump of 5 ± 1 inch to vari*

Eq. No.	Note		Const.	AAIR	$(AAIR)^{0.5}$	w/c	C_2S	C_4AF	C_3A/SO_3
1	1	ASAT	= +0.7286	−0.0740					
		s.d.	= (0.0086)	(0.0049)					
2	1	ASAT	= +0.8288		−0.1804				
		s.d.	= (0.0147)		(0.0119)				
3	1	ASAT	= +1.1607		−0.1945	−0.4915			
		s.d.	= (0.1819)		(0.0141)	(0.2685)			
4	1	ASAT	= +0.3426		−0.1626	+0.4887	+0.00428	+0.00449	
		s.d.	= (0.1751)		(0.0122)	(0.2439)	(0.00050)	(0.00162)	
5	1	ASAT	= +0.3201		−0.1628	+0.5422	+0.00419	+0.00302	−0.00633
		s.d.	= (0.1664)		(0.0116)	(0.2349)	(0.00051)	(0.00172)	(0.00253)
6	1	ASAT	= +0.3504		−0.1607	+0.4814	+0.00436	+0.00353	−0.00585
		s.d.	= (0.1609)		(0.0115)	(0.2271)	(0.00049)	(0.00168)	(0.00249)
6A	2	ASAT (odd)	= +0.4760		−0.1712	*+0.3351	+0.00421	+0.00351	−0.00793
		s.d.	= (0.2919)		(0.0191)	(0.4160)	(0.00070)	(0.00273)	(0.00395)
6B	3	ASAT (even)	= +0.2080		−0.1489	+0.6246	+0.00460	+0.00426	*−0.00229
		s.d.	= (0.2032)		(0.0152)	(0.2820)	(0.00007)	(0.00237)	(0.00344)
7	1	ASAT	= +1.380		−0.1567	+0.6202			
		s.d.	= (0.307)		(0.0118)	(0.2436)			
8	1	ASAT	= +1.469		−0.1571	+0.5556			
		s.d.	= (0.298)		(0.0116)	(0.2367)			
8A	2	ASAT (odd)	= +1.980		−0.1651	*+0.1914			
		s.d.	= (0.486)		(0.0184)	(0.4083)			
8B	3	ASAT (even)	= +1.287		−0.1488	+0.7876			
		s.d.	= (0.405)		(0.0153)	(0.2991)			

Note 1, 165 cements, Avg. = 0.6152, S.D. = 0.0851
Note 2, 83 cements
Note 3, 82 cements
*Coef./s.d. ratio less than 1.0.

ratio at the start of the freeze-thaw tests of concretes of nominal 5 ½ bags cement per various independent variables (ASAT)

CaO	SiO_2	Fe_2O_3	K_2O	MgO	Loss	Co	Ni	P	Rb	Zr	S.D.
-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	0.06400
-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	0.05596
-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	0.05583
-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	0.04483
-----	-----	-----	-----	+0.00926 (0.00291)	+0.01335 (0.00689)	-----	-----	-----	-----	-----	0.04273
-----	-----	-----	-----	+0.00868 (0.00276)	+0.01651 (0.00625)	+4.76 (2.27)	−2.653 (0.991)	+0.0540 (0.0293)	−4.64 (1.69)	−0.0880 (0.0780)	0.04062
-----	-----	-----	-----	* −0.00025 (0.00428)	+0.01539 (0.00885)	* +0.44 (5.55)	−3.627 (1.507)	+0.0640 (0.0516)	−3.19 (2.48)	−0.1360 (0.0858)	0.04238
-----	-----	-----	-----	+0.01675 (0.00366)	+0.02155 (0.00962)	+5.96 (2.52)	−1.678 (1.384)	+0.0476 (0.0360)	−6.38 (2.48)	* +0.4208 (0.6572)	0.03846
−0.0251 (0.0032)	+0.0235 (0.0030)	+0.00825 (0.00505)	−0.0424 (0.0176)	-----	-----	-----	-----	-----	-----	-----	0.04171
−0.0256 (0.0031)	+0.0241 (0.0030)	+0.00930 (0.00500)	−0.0398 (0.0186)	-----	-----	+4.18 (2.22)	−2.847 (0.968)	+0.0520 (0.0286)	−3.15 (1.82)	−0.1167 (0.0759)	0.03988
−0.0205 (0.0047)	+0.0238 (0.0041)	+0.01403 (0.00801)	−0.0558 (0.0281)	-----	-----	* −0.86 (5.39)	−3.867 (1.477)	+0.0737 (0.0502)	* −1.39 (2.59)	−0.1576 (0.0830)	0.04144
−0.0313 (0.0044)	+0.0236 (0.0045)	* +0.00272 (0.00713)	* −0.0201 (0.0269)	-----	-----	+5.48 (2.47)	−1.877 (1.355)	+0.0452 (0.0353)	−5.99 (2.77)	* +0.3715 (0.6440)	0.03848

at the start of freeze-thaw tests of concretes of nominal 5 ½ bags cement per cubic yard ous independent variables (ASAT)

CaO	SiO_2	Fe_2O_3	K_2O	MgO	Loss	Co	Ni	P	Rb	Zr	S.D.
-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	0.05509
-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	0.05488
-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	0.05449
-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	0.04395
-----	-----	-----	-----	+0.00881 (0.00279)	−0.01064 (0.00648)	-----	-----	-----	-----	-----	0.04175
-----	-----	-----	-----	+0.00827 (0.00276)	+0.01452 (0.00636)	+4.46 (2.30)	−2.244 (0.993)	+0.0625 (0.0290)	−4.10 (1.70)	−0.0980 (0.0772)	0.03993
-----	-----	-----	-----	+0.00668 (0.00412)	+0.01351 (0.00951)	* +3.22 (4.24)	* −1.573 (1.827)	+0.0968 (0.0535)	−5.08 (2.67)	−0.0906 (0.0901)	0.04268
-----	-----	-----	-----	+0.01036 (0.00418)	+0.01518 (0.00953)	+4.76 (2.91)	−2.390 (1.212)	+0.0400 (0.0365)	−2.69 (2.33)	−0.2232 (0.2066)	0.03901
−0.0235 (0.0032)	+0.0235 (0.0031)	+0.00837 (0.00504)	−0.0344 (0.0180)	-----	-----	-----	-----	-----	-----	-----	0.04085
−0.0242 (0.0031)	+0.0237 (0.0031)	+0.00918 (0.00500)	−0.0353 (0.0190)	-----	-----	+3.97 (2.26)	−2.390 (0.968)	+0.0596 (0.0283)	−2.80 (1.83)	−0.1310 (0.0749)	0.03919
−0.0267 (0.0044)	+0.0203 (0.0043)	* +0.00658 (0.00817)	−0.0942 (0.0304)	-----	-----	* +3.71 (4.02)	−2.413 (1.717)	+0.1085 (0.0501)	* −2.36 (2.65)	−0.1495 (0.0835)	0.04003
−0.0248 (0.0048)	+0.0259 (0.0047)	+0.00765 (0.00669)	* +0.0077 (0.0251)	-----	-----	+3.97 (2.80)	−2.169 (1.179)	+0.0465 (0.0354)	−3.17 (2.57)	−0.2426 (0.2003)	0.03818

to that at the beginning of freezing and thawing ranged from approximately 0.95 to less than 0.70, while those for the non-air-entrained specimens ranged from approximately 0.9 to 1.9. For the non-air-entrained concretes alone the ones that regained the greatest amounts in dynamic modulus were generally those that had lower original dynamic modulus values.

The evaluation of autogenous healing was further complicated by the fact that the specimens were seldom removed from freezing and thawing at exactly 60 percent of original E. A few were removed at 60 to 65 percent E_0 while others which were deteriorating rapidly were below 20 percent E_0 when removed. The latter were specimens which failed during the first freezing-and-thawing period and were first checked at 10 cycles. They were also specimens which showed a weight gain during freezing and thawing due to early failure. However, even these specimens reached higher dynamic modulus values after storage than they had before freezing and thawing.

No multivariable equations are given relating independent variables to regain of dynamic modulus. However, the data were subjected to analysis of variance to determine if there were significant differences in the ratios between cements. The results are shown in table 11–30 for the different

Table 11–24. *Calculated contributions of independent variables to the saturation ratio at the start of the freeze-thaw tests of concretes of nominal 5 ½ bags cement per cubic yard and a slump of 5 ± 1 inch. (ASAT)*

Independent variables	Range of variable (percent)	Coefficients from eq 6 table 11–23	Calculated contributions to ASAT	Calculated range of contributions to ASAT
			Const. = +0.35	
$(AAIR)^{0.5}$ NAE cements	0 to 2.23	−0.1607	0 to −0.36	0.36
w/c	0.6 to 0.7	+0.4814	+0.29 to +0.34	0.05
C_2S	5 to 50	+0.00436	+0.02 to +0.22	0.20
C_4AF	1 to 16	+0.00353	0 to +0.06	0.06
C_3A/SO_3	0.4 to 10.1	−0.00585	−0.02 to −0.06	0.04
MgO	0 to 5.0	+0.00827	0 to +0.04	0.04
Loss	0.3 to 3.3	+0.01452	0 to +0.05	0.05
Co**	0 to 0.01	+4.46	0 to +0.04	0.04
Ni	0 to 0.02	−2.244	0 to −0.04	0.04
P	0 to 0.5	+0.0625	0 to +0.03	0.03
Rb	0 to 0.01	−4.10	0 to −0.04	0.04
Zn**	0 to 0.5	−0.098	0 to −0.05	0.05

** Coefficient of doubtful significance as coef./s.d. rati o was less than 2.0.

Table 11–25. *Frequency distribution of cements with respect to OCYS, the number of cycles of freezing and thawing required to cause a 40-percent reduction in dynamic modulus of Series O concretes*

Type cement	Number of cycles											
	0 to 20	20 to 40	40 to 60	60 to 80	80 to 100	100 to 150	150 to 200	200 to 300	300 to 500	500 to 700	700 to 1000	Total
	Number of cements											
I	1	7	7	7	14	28	13	5				82
IA									5	3		8
II	1	8	5	9	12	24	5	4				68
IIA									1	2		3
III		3	2	2	2	4	3	4				20
IIIA										1	2	3
IV, V	1	2	4	1	4	3						15
Total	3	20	18	19	32	59	21	13	6	6	2	199

Table 11–26. *Frequency distribution of cements with respect to ACYS, the number of cycles of freezing and thawing required to cause a 40-percent reduction in dynamic modulus of Series A concretes*

Type cement	Number of cycles											
	0 to 20	20 to 40	40 to 60	60 to 80	80 to 100	100 to 150	150 to 200	200 to 300	300 to 500	500 to 700	700 to 1000	Total
	Number of cements											
I	2	5	2	13	15	21	14	6	1			79
IA								1	3	4		8
II	1	8	4	7	13	25	6	2	1			67
IIA									2	1		3
III	1	1	2	1	2	6	2	4	1			20
IIIA										1	2	3
IV, V	1	1	3	3	4	1	2					15
Total	5	15	11	24	34	53	24	13	8	6	2	195

TABLE 11–27. *"F" values for significance of reduction of variance due to added variables.*

Table	Equations*	"F" ratio	D.F.	Critical "F" ratios	
				α = 0.01	α = 0.05
11–2	0,1	118	2:177	4.70	3.04
	0,2	76.4	2:177	4.70	3.04
	1,3	15.1	6:171	2.91	2.15
	3,4	5.48	5:166	3.13	2.27
	1,5	17.8	5:172	3.12	2.27
	5,6	5.76	5:167	3.13	2.27
11–3	0,1	6.83	2:166	4.72	3.04
	0,2	19.0	2:166	4.72	3.04
	1,3	9.04	6:160	2.92	2.15
	3,4	4.01	5:155	3.14	2.27
	1,5	10.5	5:161	3.12	2.27
	5,6	4.25	5:156	3.14	2.27
11–6	0,1	118	2:173	4.71	3.04
	0,2	87.6	2:173	4.71	3.04
	1,3	21.8	4:169	3.42	2.43
	3,4	4.37	5:164	3.13	2.27
	1,5	12.5	4:169	3.42	2.43
	5,6	3.63	6:163	2.92	2.15
11–7	0,1	8.05	2:162	4.72	3.04
	0,2	20.4	2:162	4.72	3.04
	1,3	10.7	4:158	3.43	2.43
	3,4	3.53	5:153	3.14	2.27
	1,5	11.2	4:158	3.43	2.43
	5,6	3.07	6:152	2.92	2.15
11–10	0,1	21.0	2:178	4.70	3.04
	1,2	18.9	4:174	3.14	2.43
	2,3	5.9	4:170	3.14	2.43
	1,4	13.1	6:172	2.91	2.15
	4,5	4.95	5:167	3.13	2.27
11–11	0,1	0.92	2:166	4.72	3.04
	1,2	17.2	4:162	3.14	2.43
	2,3	6.46	4:158	3.14	2.43
	1,4	12.0	6:160	2.92	2.15
	4,5	5.46	5:155	3.14	2.27
11–14	0,1	3.46	2:174	4.71	3.04
	0,2	9.09	2:174	4.71	3.04
	2,3	16.5	4:170	3.14	2.43
	3,4	4.46	4:166	3.14	2.43
	2,5	16.6	4:170	3.14	2.43
	5,6	4.48	4:166	3.14	2.43
11–15	0,3	10.3	6:158	2.92	2.15
	3,4	5.20	4:154	3.14	2.43
	0,5	10.3	6:158	2.92	2.15
	5,6	5.21	4:154	3.14	2.43
11–18	0,1	115	2:176	4.71	3.04
	0,2	140	2:176	4.71	3.04
	2,3	40.1	2:174	4.71	3.04
	3,4	3.81	2:172	4.71	3.04
	2,4	22.6	4:172	3.14	2.43
	4,5	3.55	4:168	3.14	2.43
	2,6	30.5	3:173	3.88	2.67
	6,7	2.83	5:168	3.13	2.27
11–19	0,1	51.1	2:164	4.71	3.04
	0,2	54.2	2:164	4.71	3.04
	2,3	35.6	2:162	4.71	3.04
	3,4	2.98	2:160	4.71	3.04
	2,4	19.7	4:160	3.42	2.43
	4,5	3.84	4:156	3.42	2.43
	2,6	27.4	3:161	3.88	2.67
	6,7	2.58	5:156	3.13	2.43
11–22	0,1	173	2:175	4.70	3.04
	0,2	253	2:175	4.70	3.04
	2,4	33.6	3:172	3.88	2.67
	4,5	6.77	3:169	3.88	2.67
	5,6	4.60	5:164	3.13	2.27
	3,7	35.4	4:170	3.42	2.43
	7,8	4.18	5:159	3.17	2.27
11–23	0,1	115	2:163	4.72	3.04
	0,2	117	2:163	4.72	3.04
	2,4	31.4	3:160	3.88	2.67
	4,5	6.77	3:157	3.88	2.67
	5,6	3.93	5:152	3.14	2.43
	3,7	32.6	4:158	3.43	2.43
	7,8	3.73	5:153	3.14	2.43

* 0 in the equation column refers to the D.D. value of the corresponding dependent variable as given in footnotes in the tables of equations.

TABLE 11–28. *Autogenous healing—actual elapsed time*

Nominal time, years	Actual elapsed time, months
1	16.1 to 16.4
2	20.1 to 24.8
3	33.2 to 38.2
4	48.9 to 51.2
5	57.5 to 60.4

TABLE 11–29. *Autogenous healing—average ratios of dynamic modulus after storage to that after freezing and thawing*

Time, years	Cement type	*n*	Average	S.D.
1	NAE	42	2.38	0.60
2	NAE	477	2.34	1.46
3	NAE	302	2.20	0.82
4	NAE	59	2.81	1.81
5	NAE	24	2.15	1.78
2	AE	31	1.34	0.14
3	AE	14	1.32	0.14

TABLE 11–30. *Autogenous healing—ANOVA for differences between cements—ratio of dynamic modulus*

Time, years	Cement type		*n*	S.S.	M.S.	F	F crit.
1	NAE	Between cements	8	8.7578	1.0947	6.92	2.30
		Within cements	27	4.2729	0.1583		
		Total	35	13.0307			
2	NAE	Between cements	109	480.643	4.4096	10.32	1.30
		Within cements	330	140.984	0.4272		
		Total	439	621.627			
3	NAE	Between cements	69	108.240	1.5687	3.64	1.37
		Within cements	210	90.559	0.4312		
		Total	279	198.799			
5	NAE	Between cements	4	29.0017	7.2504	2.37	3.06
		Within cements	15	45.9077	3.0605		
		Total	19	74.9094			
2	AE	Between cements	5	0.0869	0.0174	1.19	2.77
		Within cements	18	0.2637	0.0146		
		Total	23	0.3506			
3	AE	Between cements	3	0.2485	0.0828	15.33	3.71
		Within cements	10	0.0540	0.0054		
		Total	13	0.3025			

nominal ages for air-entrained and non-air-entrained cements.

There were no significant differences between the O-series and A-series concretes within cements. Therefore the data for the four specimens for each cement were combined in determining the within-cement variance. The critical values in column 8 headed F crit. are those which must be equalled or exceeded by the F ratios in column 7 to indicate a significant difference between cements at the 5.0 percent significance level.

For the non-air-entrained cements, there were significant differences at the nominal 1-, 2-, and 3-year periods of storage, but not at 5 years. The data for 4 years could not be subjected to this analysis because they did not include groups from the same cement, but were mainly individual values.

For the air-entrained cements a significant difference was indicated at 3 years but not at 2.

7. Discussion

7.1. Durability

Tables 11–31 amd 11–32 show selected equations for the various independent variables for the

TABLE 11–31. *Coefficients, coef./s.d. ratios and calculated contributions of independent variables associated with durability, weight loss, and saturation ratio (Series O concretes made of AE + NAE cements)*

Column	1	2	3
Eq. No.	4	3	5
Table No.	11–3	11–12	11–20
Dependent variable	ODUR	OWTL	OSAT
Constant	+88.6	−1.15	+0.586
Air content, coef.	+8.89	+1.42	[1] −0.145
coef./s.d.	20.8	10.0	18.7
Calculated range	89	14.2	0.46
C_3A, coef.		+0.411	
coef./s.d.		4.0	
Calculated range		5.8	
C_3S, coef.	−0.53		
coef./s.d.	1.9		
Calculated range	24		
C_2S, coef.	−0.817		+0.0044
coef./s.d.	3.1		8.0
Calculated range	37		0.20
C_4AF, coef.		+0.753	+0.0054
coef./s.d.		5.7	3.1
Calculated range		11	0.08
Na_2O, coef.	−8.26	−3.71	
coef./s.d.	1.9	2.5	
Calculated range	6	2.6	
K_2O, coef.	−20.3	−8.44	
coef./s.d.	4.8	6.3	
Calculated range	22	9.3	
MgO, coef.	−2.75		+0.0094
coef./s.d.	3.9		2.9
Calculated range	14		0.05
APF, coef.	−0.0031		
coef./s.d.	2.1		
Calculated range	9		
Loss, coef.			+0.0166
coef./s.d.			2.3
Calculated range			0.05
Ba, coef.	−40.2		
coef./s.d.	1.9		
Calculated range	8		
Cu, coef.	−210		+0.916
coef./s.d.	2.5		2.0
Calculated range	11		0.05
Mn, coef.			−0.063
coef./s.d.			1.4
Calculated range			0.06
P, coef.			+0.044
coef./s.d.			1.3
Calculated range			0.02
Pb, coef.	−208	−86	
coef./s.d.	1.8	2.1	
Calculated range	10	4.3	
Rb, coef.	−1068	−315	+3.65
coef./s.d.	2.5	2.6	1.9
Calculated range	11	3.2	0.04
Ti, coef.	−14.0	−6.35	
coef./s.d.	2.3	3.1	
Calculated range	1.4	6.4	
Zr, coef.		+11.2	
coef./s.d.		1.8	
Calculated range		5.6	

[1] $(OAIR)^{0.5}$.

TABLE 11–32. *Coefficients, coef./s.d. ratios, and calculated contributions of independent variables associated with durability, weight loss, and saturation ratio (Series A concretes made of AE + NAE cements)*

Column	1	2	3
Eq. No.	4	4	5
Table No.	11–8	11–16	11–24
Dependent variable	ADUR	AWTL	ASAT
Constant	+52.38	+1.157	+0.2441
Air content, coef.	+7.82	+0.902	−0.1456 [1]
coef./s.d.	18.4	7.0	15.1
Calculated range	78	9.0	0.46
w/c, coef.			+0.588
coef./s.d.			2.6
Calculated range			0.10
C_3A, coef.		+0.5275	
coef./s.d.		4.9	
Calculated range		7.4	
C_2S, coef.	−0.4679		+0.00468
coef./s.d.	3.9		9.7
Calculated range	21		0.21
C_4AF, coef.		+0.6059	+0.00408
coef./s.d.		4.3	2.4
Calculated range		9.1	0.06
Na_2O, coef.		+2.527	
coef./s.d.		1.6	
Calculated range		1.8	
K_2O, coef.	−15.93	−9.70	
coef./s.d.	3.6	7.0	
Calculated range	18	1.1	
MgO, coef.	−2.378		+0.00868
coef./s.d.	3.2		3.1
Calculated range	12		0.04
APF, coef.	−0.00297		
coef./s.d.	1.8		
Calculated range	9		
C_3A/SO_3, coef.			−0.00461
coef./s.d.			1.9
Calculated range			0.45
Loss. coef.			+0.1651
coef./s.d.			2.6
Calculated range			0.50
Ba, coef.	−47.94		
coef./s.d.	2.0		
Calculated range	10		
Co, coef.			+4.76
coef./s.d.			2.1
Calculated range			0.05
Cu, coef.	−232.0		
coef./s.d.	2.5		
Calculated range	12		
Mn, coef.		−4.903	
coef./s.d.		2.3	
Calculated range		4.9	
Ni, coef.			−2.653
coef./s.d.			2.7
Calculated range			0.04
P, coef.			+0.054
coef./s.d.			1.8
Calculated range			0.03
Pb, coef.	−204.1	−52.54	
coef./s.d.	1.6	1.3	
Calculated range	10	2.6	
Rb, coef.	−895.2	−329.2	−4.64
coef./s.d.	1.9	2.2	2.7
Calculated range	9	3.3	0.05
Ti, coef.	−12.55	−4.379	
coef./s.d.	1.4	2.0	
Calculated range	13	4.4	
Zr, coef.			−0.088
coef./s.d.			1.1
Calculated range			0.04

[1] $(AAIR)^{0.5}$.

Series O and Series A concretes respectively with both air-entraining and non-air-entraining cements included. The equations are presented vertically instead of horizontally as in the previous tables. Coef./s.d. ratios to indicate the probable significance of the coefficients, and the calculated ranges of the contributions of the different independent variables are also given.

Comparison of the coefficients in the three columns of table 11–31 shows that higher air content was associated with all three of the dependent variables: durability factor, weight loss, and saturation ratio. In each case the coef./s.d. ratio was 10.0 or greater. Durability factor and weight loss are related effects, since specimens which remain in the freezing-and-thawing test longer, thus having higher durability factors, also lose more weight by sloughing. Thus, all the independent variables that appear in both columns 1 and 2 have the same sign in both. The degree of saturation at the time freezing-and-thawing tests start has a significant effect on length of time in the freezing-and-thawing test, and thus on both durability factor and weight loss. Note that all of the coefficients for independent variables that appear in column 3 as well as in either 1 or 2, with one exception, have opposite signs in column 3 to the ones in columns 1 and 2, indicating that factors that are associated with a higher degree of saturation are associated with lower durability and weight loss. Part of the correlation between saturation and air content is due to the fact that the percentage of air is included in the calculation of the saturation ratio.

The independent variables, other than air content, that showed a significant association with two or more of the dependent variables in columns 1, 2, and 3, were C_2S, C_4AF, K_2O, MgO, Cu, Rb, and Ti, with possibly Na_2O and Pb added.

Cements with high C_2S, MgO, and Cu were associated with concretes having high saturation ratios and low durability factors. However, high C_4AF, which was associated with high saturation ratio, was also associated with high weight loss but showed no significant association with durability factor. This suggests that, if these associations result from real cause and effect relationships, the mechanism by which C_4AF affects the saturation ratio differs from that by which the other independent variables affect it. Increasing loss on ignition was also significantly associated with increasing saturation ratio, but showed no significant association with either durability factor or weight loss. Increases in both the two alkalis showed significant associations with decrease in weight loss, but neither had a significant relationship to saturation ratio, and only K_2O had a significant negative association with durability factor. The coefficient for Na_2O was negative, but the coef./s.d. ratio was only 1.9. It is possible that the apparent difference between the two alkalis is due to the wider range of values that existed for K_2O as compared to Na_2O (1.1 percent compared to 0.7 percent, respectively).

Experience in the laboratory and in the field has demonstrated repeatedly and conclusively that if the objective is to produce concrete which will resist damage from freezing and thawing, so far as the paste is concerned, the easiest, cheapest, and surest way to accomplish that end, assuming the concrete is well-designed in other respects, made with good materials, and properly cured, is by the incorporation in the concrete of an adequate system of entrained air voids [2, 5]. Previous studies have indicated that, although changes in composition, fineness, or other properties of the cement may cause significant changes in durability of non-air-entrained concretes, the increase in durability produced by entrained air is so dramatic that the effects of properties of the cement are overshadowed. There is nothing in the results of the present study that changes this picture in any essential manner, although the data do serve to round out some details, thanks mainly to the large number of cements tested. One result from this study is that indications are given of what independent variables may be related to durability of non-air-entrained concretes and to what degree. No indications, unfortunately, are given as to possible relationships in air-entrained concretes directly, because of the small number of air-entraining cements tested.

The above conclusions are based on the following features of the results with the Series O concretes, with a nominal 5½ bags of cement per cubic yard and a water-cement ratio of 0.635. (Results with the A series with constant slump are similar.)

Table 11–1 shows that all concretes made with non-air-entraining cements had durability factors less than 60, which means that they all suffered a 40-percent reduction in dynamic modulus in less than 300 cycles of freezing and thawing. All of the concretes made with air-entraining cements, however, had durability factors greater than 60, and required from about 300 to almost 1000 cycles of freezing and thawing to produce a 40-percent reduction in dynamic *E*.

In table 11–3, for non-air-entrained cements only, eq 1 relates only one independent variable, air content of the concretes, to the durability factor in the laboratory freezing-and-thawing test. The coefficient for air content is highly significant, being about 3½ times its estimated standard deviation, and a significant reduction in the overall S.D. occurs, from 11.22 to 10.85. When six more independent variables are included in the analysis (eq 3) a further significant decrease in S.D. occurs, and all of the added coefficients are greater in magnitude than their s.d.'s, although only three of them have coef./s.d. ratios greater than or equal to 2. In eq 4 with five of the trace elements included as independent variables, a further significant reduction in S.D. occurs; all of the added variables have coefficients greater in

magnitude than their s.d.'s with three being greater than two times the s.d.; and coef./s.d. ratios for the previously included independent variables are as great as or greater than the corresponding ones in eq 3. Also, in going from eq 1 to eq 3 and then to eq 4, there is a progressive increase in both coefficient and coef./s.d. ratio for the air content. To summarize, although there was a significant relationship between the durability factor and air content for the non-air-entraining cements, there was an additional significant correlation with seven out of eleven additional independent variables, after the correlation with air content was accounted for.

Turning to table 11–2 where data for 12 air-entrained cements are included with the 168 non-air-entrained cements represented in table 11–4, remarks similar to those given above apply to comparisons between eq 1, 3, and 4. However, there are interesting differences between corresponding equations in the two tables. In the first place, the coefficients for air content in table 11–2 are larger than those in the corresponding equations in table 11–3, and their s.d.'s are smaller, thus causing a large increase in coef./s.d. ratio. These ratios are 3.6, 5.2, and 6.4 for eq 1, 3, and 4, respectively, in table 11–3; and 17., 20., and 21. for the corresponding equations in table 11–2. This, of course, shows the large effect of entrained air on durability. In general, however, the coefficients and coef./s.d. ratios for the other independent variables in eq 3 and 4, table 11–2 are about the same as the corresponding ones in table 11–3, with the same ones being significant in both cases. This may be explained by the fact that the added data for the independent variables other than air content were generally in the same range for the twelve air-entraining cements as for the non-air-entraining cements, while the values for air content were much higher. However, it is of interest that, even with the increase in average durability and in significance of the air content, the other independent variables still show significant correlations. It is, of course, impossible from the evidence given here to predict what would happen if a much larger number of air-entraining cements had been included, or if air-entraining cements alone had been subjected to the same type of analysis.

Statistically significant relationships, of course, do not in themselves constitute evidence of cause-and-effect relationships between variables. It is well known from experimental evidence that entrained air is a cause of increased durability, and much research has gone into investigation of the physical reasons for the effect. So far as the statistical correlations between durability and the other independent variables discussed here are concerned, however, there is no such body of knowledge available. Whether or not any of the relationships indicated are direct effects, or whether they have an indirect effect on durability through their effect on some other variable, or whether the indicated correlation is gratuitous, can not be determined positively. Two hypotheses that appear plausible, however, and are capable of some investigation on the basis of the data obtained in this study, are that some of the independent variables other than air content may affect durability indirectly through their effect on the system of entrained air voids or through their effect on the degree to which the concretes took up water during the soaking period that preceded freezing.

The equations shown in tables 11–33 through 11–36 were calculated to investigate these hypotheses further. These tables give results for the O- and A-series concretes, with and without the air-entraining cements. The seven equations in each of the four tables all include the same set of independent variables as those in eq 4, tables 11–2 and 11–3. Also the same 177 cements are included in tables 11–33 and 11–34 and the same 165 cements in tables 11–35 and 11–36. Thus comparisons may easily be made of the effects of using different dependent variables or of adding air content, saturation ratio, or both as independent variables.

Equation 4 in all four tables shows the relationship of the basic set of eleven independent variables to durability factor of the concretes with no other independent variables included. In the equations with all cements (tables 11–33 and 11–34) the only independent variables which had coef./s.d. ratios greater than 1.0 were C_2S, Rb, and Cu; and Rb was the only one whose ratio was greater than 2.0. For the non-air-entraining cements only, there was a difference between the series O concretes (table 11–35) and the series A concretes (table 11–36). In the former, three of the coef./s.d. ratios, C_2S, K_2O, and MgO, were greater than 2.0, and four others were greater than 1.0. In table 11–36 six coef./s.d. ratios were greater than 1.0, but none was greater than 2.0. All of the coef./s.d. ratios that were greater than 1.0 in eq 4, table 11–35, decreased in table 11–36. This indicates an effect of water-cement ratio which will be discussed further below. Note that all of the coefficients whose coef./s.d. ratios were greater than 1.0 in each of the eqs 4 were negative, indicating that increases in these variables were related to decreases in durability factor.

7.2. Effect of Alkalis on Durability

Equations 1 and 2 in all four of the tables (11–33 through 11–36) show relationships between the same set of independent variables as those in eq 4 and air content and saturation ratio of the concretes, respectively. In eqs 1 for air content, the coef./s.d. ratios for both Na_2O and K_2O are greater than 2.0 in all cases. In fact, the coef./s.d. ratios for K_2O in all four cases and for Na_2O with the non-air-entraining cements were greater than 3.0. The coefficients are all positive also, indicating that increases in the alkalis were significantly related to increased air content.

TABLE 11–33. *Relationship of durability factor, air content, and saturation ratio to various independent variables; O series concretes, air-entraining and non-air-entraining cements*

Column	1	2	3	4	5	6	7
Dependent Variable	OAIR	OSAT	OAIR	ODUR	ODUR	ODUR	ODUR
Constant	−0.890	0.637	9.20	80.8	88.4	176.	111.
Air content							
coef.					8.52		7.02
s.d.					0.422		0.667
coef./s.d.					20.2		10.5
Saturation ratio							
coef.			−15.8			−150.	−38.4
s.d.			0.974			10.75	13.5
coef./s.d.			16.3			13.9	2.86
C_3S							
coef.	0.00236	−0.000954	−0.0128	−0.502	−0.522	0.645	−0.556
s.d.	0.0546	0.00271	0.0339	0.551	0.296	0.374	0.290
coef./s.d.	0.043	0.35	0.38	0.91	1.77	1.72	1.92
C_2S							
coef.	−0.00461	0.00425	0.0627	−0.915	−0.876	−0.279	−0.719
s.d.	0.0502	0.00249	0.0314	0.506	0.272	0.347	0.272
coef./s.d.	0.092	1.71	2.00	1.81	3.22	0.80	2.65
Na_2O							
coef.	1.779	−0.0746	0.600	6.81	−8.34	−4.35	−8.54
s.d.	0.823	0.0408	0.516	8.30	4.52	5.69	4.42
coef./s.d.	2.16	1.83	1.16	0.82	1.85	0.76	1.93
K_2O							
coef.	2.51	−0.1070	0.818	1.31	−20.1	−14.7	−20.4
s.d.	0.787	0.0390	0.499	7.94	4.39	5.51	4.30
coef./s.d.	3.19	2.74	1.64	0.17	4.58	2.67	4.75
MgO							
coef.	0.176	−0.000798	0.164	−0.807	−2.31	−0.927	−2.08
s.d.	0.133	0.00658	0.0824	1.34	0.723	0.909	0.712
coef./s.d.	1.33	0.12	1.99	0.60	3.20	1.02	2.92
APF							
coef.	0.000265	−0.00000909	0.000121	−0.000702	−0.00296	−0.00206	−0.00291
s.d.	0.000286	0.0000143	0.000178	0.00289	0.00155	0.00196	0.00152
coef./s.d.	0.93	0.64	0.68	0.24	1.90	1.05	1.91
Ba							
coef.	1.038	−0.0363	0.463	−28.2	−37.0	−33.6	−36.8
s.d.	4.15	0.206	2.58	41.8	22.5	28.4	22.0
coef./s.d.	0.25	0.18	0.18	0.67	1.64	1.18	1.67
Rb							
coef.	−168.	1.063	−151.	−2416.	−984.	−2257.	−1195.
s.d.	79.2	3.93	49.2	799.	435.	543.	432.
coef./s.d.	2.12	0.27	3.08	3.02	2.26	4.16	2.77
Pb							
coef.	5.07	−0.387	−1.063	−171.	−214.	−229.	−221.
s.d.	22.4	1.109	13.9	225.	121.	153.	119.
coef./s.d.	0.23	0.35	0.077	0.76	1.77	1.49	1.87
Ti							
coef.	1.46	−0.0711	0.335	0.936	−11.50	−9.70	−12.0
s.d.	1.17	0.0580	0.729	11.79	6.36	8.05	6.23
coef./s.d.	1.25	1.23	0.46	0.079	1.81	1.21	1.93
Cu							
coef.	−4.10	1.135	13.9	−229.	−194.	−58.7	−156.
s.d.	16.1	0.796	10.02	162.	87.0	111.	86.1
coef./s.d.	0.26	1.43	1.38	1.41	2.23	0.53	1.81

The question arises, if increased alkali content was associated with increased air content, why was it not also associated with a higher durability factor? Looking at the coefficients for the two alkalis in eq 2 in all four tables, we find that all eight of the coef./s.d. ratios were greater than 1.0, and all but three of these were greater than 2.0. The coefficients, however, are all negative, indicating that a decrease in saturation ratio was associated with increases in alkali content. This again might be expected to indicate that increases in alkali content should be associated with increased durability.

In eq 3 with air content as the dependent variable and saturation ratio included as an independent variable, the coef./s.d. ratios for the alkalis are consistently reduced and remain significant only for the non-air-entrained cements.

Comparing eq 4, in which durability factor is related only to the basic set of 11 independent variables, with eq 5, 6, and 7, in which air content alone, saturation ratio alone, and both together are included as independent variables, shows that whatever relationship existed between the basic independent variables in these equations and durability was influenced by their relationship with air content and saturation ratio. Of the 148 coefficients for independent variables (not counting the constant terms) in eqs 5, 6, and 7, only six had coef./s.d. ratios less than 1.0, but 66, or about 45 percent had coef./s.d. ratios greater than 2.0.

For the alkalis specifically, note that in eq 4

TABLE 11–34. *Relationship of durability factor, air content and saturation ratio to various independent variables; A series concretes, air-entraining and non-air-entraining cements*

Column	1	2	3	4	5	6	7
Dependent variable	AAIR	ASAT	AAIR	ADUR	ADUR	ADUR	ADUR
Constant	−3.91	−0.845	10.59	60.1	88.2	180.	135.
Air content							
coef.	----------	----------	----------	----------	7.17	----------	4.25
s.d.	----------	----------	----------	----------	0.431	----------	0.778
coef./s.d.	----------	----------	----------	----------	16.6	----------	5.47
Saturation ratio							
coef.	----------	----------	−17.2	----------	----------	−142.	−69.1
s.d.	----------	----------	0.827	----------	----------	8.93	15.7
coef./s.d.	----------	----------	20.8	----------	----------	15.9	4.40
C_3S							
coef.	0.0249	−0.00254	−0.0188	−0.249	−0.427	−0.610	−0.530
s.d.	0.0618	0.00306	0.326	0.559	0.342	0.352	0.325
coef./s.d.	0.40	0.83	0.58	0.45	1.25	1.73	1.63
C_2S							
coef.	0.0298	0.00224	0.0683	−0.682	−0.896	−0.364	−0.654
s.d.	0.0568	0.00282	0.0300	0.514	0.314	0.324	0.303
coef./s.d.	0.53	0.80	2.28	1.33	2.85	1.12	2.16
Na_2O							
coef.	1.87	−0.130	−0.344	5.77	−7.62	−12.5	−11.08
s.d.	0.930	0.0461	0.501	8.41	5.21	5.42	5.00
coef./s.d.	2.01	2.79	0.69	0.69	1.46	2.32	2.22
K_2O							
coef.	2.98	−0.162	0.196	1.90	−19.5	−21.1	−22.0
s.d.	0.890	0.0441	0.487	8.05	5.09	5.26	4.86
coef./s.d.	3.35	3.68	0.40	0.24	3.83	4.02	4.53
MgO							
coef.	0.262	−0.00318	0.207	−0.306	−2.18	−0.758	−1.64
s.d.	0.150	0.00744	0.0791	1.36	0.838	0.854	0.804
coef./s.d.	1.74	0.43	2.62	0.23	2.61	0.89	2.04
APF							
coef.	0.000377	−0.0000133	0.000149	−0.000381	−0.00309	−0.00227	−0.00290
s.d.	0.000324	0.0000160	0.000171	0.00293	0.00180	0.00184	0.00170
coef./s.d.	1.17	0.83	0.88	0.13	1.72	1.23	1.70
Ba							
coef.	2.88	−0.288	−2.06	−20.4	−41.1	−61.3	−52.5
s.d.	4.69	0.233	2.48	42.4	26.0	26.8	24.8
coef./s.d.	0.61	1.24	0.83	0.48	1.58	2.29	2.12
Rb							
coef.	−184.	0.915	−168.	−2241.	−925.	−2111.	−1397.
s.d.	89.6	4.44	47.2	810.	502.	510.	488.
coef./s.d.	2.05	0.21	3.56	2.77	1.84	4.14	2.86
Pb							
coef.	11.7	−1.153	−8.09	−106.2	−190.	−270.	−236.
s.d.	25.3	1.25	13.3	229.	140.	144.	133.
coef./s.d.	0.46	0.92	0.61	0.46	1.36	1.87	1.77
Ti							
coef.	2.09	−0.1172	0.0825	3.88	−11.13	−12.8	−13.1
s.d.	1.32	0.0656	0.703	11.96	7.37	7.59	7.00
coef./s.d.	1.58	1.79	0.12	0.32	1.15	1.68	1.87
Cu							
coef.	−7.08	0.768	6.10	−275.	−225.	−166.	−192.
s.d.	18.2	0.900	9.58	164.	100.4	103.5	95.5
coef./s.d.	0.39	0.85	0.64	1.68	2.24	1.16	2.01

only one of the eight coef./s.d. ratios is greater than 2.0, and only two others greater than 1.0. However, in eqs 5, 6, and 7 in the four tables, 22 of the 24 coefficients for the two alkalis are greater than 1.0 and 14 of these are greater than 2.0.

It has been established by research over a number of years that the beneficial effect of entrained air on the durability of concrete depends not only on the amount of air present, but also on the character of the distribution of that air throughout the paste matrix [16, 17, 18, 19]. For the air to be effective in preventing the build-up of pressures which can cause disruption of the paste during freezing, a significantly large proportion of the total volume of air needs to be present in the form of small discrete bubbles, evenly distributed throughout the paste. Two parameters of the air void system in the hardened concrete which are of importance in relation to the efficacy of that system in providing protection from frost damage are: (1) the specific surface, α, which is a measure of the ratio of total surface area of the voids to their total volume, and (2) spacing factor, $\bar{L}$, which is a measure of the average distance between adjacent bubbles in the paste, and thus of the average distance water has to travel in the paste to a bubble where it can freeze without causing trouble. Large α and small $\bar{L}$ are related to better frost resistance of the concrete.

The results of studies by Mielenz and others

TABLE 11–35. *Relationship of durability factor, air content, and saturation ratio to various independent variables; O series concretes, non-air-entraining cements.*

Column	1	2	3	4	5	6	7
Dependent variable	OAIR	OSAT	OAIR	ODUR	ODUR	ODUR	ODUR
Constant	−1.59	0.638	2.62	80.2	91.4	129.	119.
Air content							
coef.	----------	----------	----------	----------	7.00	----------	3.74
s.d.	----------	----------	----------	----------	1.10	----------	1.39
coef./s.d.	----------	----------	----------	----------	6.36	----------	2.69
Saturation ratio							
coef.	----------	----------	−6.61	----------	----------	−76.4	−51.8
s.d.	----------	----------	0.634	----------	----------	11.07	14.2
coef./s.d.	----------	----------	10.4	----------	----------	6.91	3.65
C_3S							
coef.	0.0267	−0.00153	0.0166	−0.343	−0.530	−0.461	−0.523
s.d.	0.0224	0.00219	0.0172	0.342	0.306	0.300	0.295
coef./s.d.	1.20	0.70	0.97	1.004	1.73	1.54	1.77
C_2S							
coef.	0.01104	0.00391	0.0368	−0.777	−0.854	−0.478	−0.616
s.d.	0.021	0.00201	0.0159	0.314	0.280	0.278	0.277
coef./s.d.	0.54	1.95	2.31	2.48	3.05	1.72	2.22
Na_2O							
coef.	1.056	−0.0495	0.729	0.412	−6.98	−3.37	−6.10
s.d.	0.331	0.0323	0.255	5.06	4.66	4.46	4.48
coef./s.d.	3.19	1.53	2.85	0.082	1.50	0.76	1.36
K_2O							
coef.	1.114	−0.0614	0.708	−10.44	−18.2	−15.1	−17.8
s.d.	0.324	0.0317	0.251	4.95	4.58	4.39	4.41
coef./s.d.	3.44	1.94	2.82	2.11	3.98	3.45	4.03
MgO							
coef.	0.0478	0.00357	0.0714	−2.13	−2.46	−1.85	−2.12
s.d.	0.0544	0.00532	0.0418	0.832	0.744	0.729	0.721
coef./s.d.	0.88	0.67	1.71	2.55	3.31	2.54	2.94
APF							
coef.	0.000115	−0.00000169	0.000104	−0.00265	−0.00346	−0.00278	−0.00317
s.d.	0.000117	0.0000114	0.0000895	0.00179	0.00160	0.00156	0.00154
coef./s.d.	0.99	0.15	1.16	1.48	2.16	1.78	2.06
Ba							
coef.	2.78	−0.109	2.06	−16.6	−36.0	−24.9	−32.6
s.d.	1.65	0.161	1.26	25.2	22.7	22.1	21.8
coef./s.d.	1.69	0.68	1.63	0.66	1.59	1.13	1.50
Rb							
coef.	45.7	−6.01	6.01	−590.	−910.	−1050.	−1072.
s.d.	32.4	3.16	25.1	494.	444.	438.	429.
coef./s.d.	1.41	1.90	0.24	1.19	2.05	2.40	2.50
Pb							
coef.	7.21	−0.469	4.11	−149.	−199.	−184.	−200.
s.d.	8.85	0.864	6.79	135.	121.	118.	116.
coef./s.d.	0.81	0.54	0.61	1.10	1.65	1.56	1.72
Ti							
coef.	0.915	−0.0553	0.550	−5.89	−12.3	−10.1	−12.2
s.d.	0.479	0.0468	0.369	7.32	6.60	6.43	6.35
coef./s.d.	1.91	1.18	1.49	0.81	1.86	1.57	1.92
Cu							
coef.	15.4	0.440	18.3	−62.1	−170.	−28.5	−96.9
s.d.	6.40	0.625	4.92	97.9	88.9	85.8	87.8
coef./s.d.	2.41	0.70	3.72	0.63	1.91	0.33	1.10

[20] on the mechanisms by which air-entraining agents facilitate the production of an efficacious air void system in hardened concrete, provide possible explanations for some of the trends shown by these data. In plastic concrete, the air in smaller voids, which are those mainly responsible for the increased durability of air-entrained concrete, is under greater pressure than that in larger voids. The tendency is for air in the smaller voids to dissolve in the water in the mix until the latter becomes saturated and then for air to be released from the solution into larger voids which are under lower pressure [21]. Thus, while the concrete is still plastic, larger air bubbles tend to grow at the expense of smaller bubbles producing an increase in total air content (providing too many of the large bubbles do not escape from the surface), a decrease in specific surface α of the air void system, and an increase in the spacing factor $\bar{L}$. The effect of a good air-entraining agent is to change conditions at the air-water interface in such a way as to decrease the rate of transfer of air from smaller bubbles to larger ones, and thus to preserve the system of smaller bubbles which is effective in producing increased frost resistance.

Mielenz, et al, [20] show that certain constituents that may be introduced by the cement and certain characteristics of the concrete mixes or their handling prior to hardening, have an effect on the operation of air-entraining agents. Their

TABLE 11–36. *Relationship of durability factor, air content, and saturation ratio to various independent variables; A series concretes, non-air-entraining cements*

Column	1	2	3	4	5	6	7
Dependent variable	AAIR	ASAT	AAIR	ADUR	ADUR	ADUR	ADUR
Constant	−3.94	0.825	3.28	68.7	97.1	142.	136.
Air content							
coef.					7.19		1.87
s.d.					1.04		1.65
coef./s.d.					6.92		1.14
Saturation ratio							
coef.			−8.75			−89.1	−72.7
s.d.			0.533			10.9	18.1
coef./s.d.			16.4			8.21	4.03
C_3S							
coef.	0.0444	−0.00301	0.0181	−0.213	−0.532	−0.481	−0.515
s.d.	0.0255	0.00233	0.0154	0.374	0.331	0.314	0.315
coef./s.d.	1.74	1.29	1.17	0.57	1.61	1.53	1.63
C_2S							
coef.	0.0348	0.00211	0.0533	−0.631	−0.881	−0.443	−0.543
s.d.	0.0234	0.00213	0.0141	0.343	0.302	0.287	0.300
coef./s.d.	1.49	0.99	3.77	1.84	2.91	1.54	1.81
Na_2O							
coef.	1.170	−0.103	0.270	0.439	−7.97	−8.73	−9.23
s.d.	0.376	0.0344	0.233	5.53	4.99	4.75	4.77
coef./s.d.	3.11	2.99	1.16	0.79	1.60	1.84	1.94
K_2O							
coef.	1.42	−0.105	0.500	−9.03	−19.2	−18.4	−19.3
s.d.	0.369	0.0337	0.229	5.42	4.96	4.66	4.73
coef./s.d.	3.84	3.10	2.18	1.67	3.87	3.93	4.08
MgO							
coef.	0.0992	0.00282	0.124	−1.81	−2.52	−1.56	−1.79
s.d.	0.0619	0.00566	0.0373	0.910	0.803	0.761	0.787
coef./s.d.	1.60	0.50	3.32	1.99	3.14	2.05	2.28
APF							
coef.	0.000211	−0.00000460	0.000171	−0.00243	−0.00395	−0.00284	−0.00316
s.d.	0.000133	0.0000121	0.0000801	0.00195	0.00172	0.00163	0.00165
coef./s.d.	1.59	0.38	2.14	1.25	2.29	1.74	1.91
Ba							
coef.	4.88	−0.374	1.61	−9.40	−44.5	−42.7	−45.7
s.d.	1.87	0.171	1.15	27.5	24.6	23.3	23.5
coef./s.d.	2.60	2.18	1.40	0.34	1.81	1.83	1.95
Rb							
coef.	49.7	−7.70	−17.7	−560.	−918.	−1247.	−1214.
s.d.	36.8	3.36	22.6	541.	476.	459.	460.
coef./s.d.	1.35	2.29	0.78	1.04	1.93	2.71	2.65
Pb							
coef.	15.0	−1.28	3.78	−75.4	−183.	−190.	−197.
s.d.	10.07	0.920	6.10	148.	130.	124.	124.
coef./s.d.	1.49	1.39	0.62	0.51	1.41	1.53	1.58
Ti							
coef.	1.35	−0.0921	0.547	−4.38	−14.1	−12.6	−13.6
s.d.	0.545	0.0498	0.332	8.00	7.14	6.76	6.81
coef./s.d.	2.48	1.85	1.65	0.55	1.98	1.86	2.00
Cu							
coef.	15.3	−0.0561	14.8	−123.	−232.	−128.	−155.
s.d.	7.29	0.666	4.39	107.	95.0	89.4	92.6
coef./s.d.	2.10	0.084	3.37	1.15	2.45	1.43	1.68

work was done mainly on neat cement slurries and pastes to which air-entraining agents had been added, while the work reported here was done on concretes most of which were made with non-air-entraining cements. However, the fact that many of the effects detected with our data are compatible with the explanations given by Mielenz, et al., and these comparisons tend to be reinforced when the twelve air-entraining cements are included in the analysis appears to be worthy of consideration. There are substances which may accidentally or purposefully (such as grinding aids) become incorporated in a non-air-entraining cement which may act to some extent as air-entraining agents, and if such substances are present, then the effects shown in Mielenz work might explain some of our indicated relationships. Unfortunately measurements on the air-void systems in the hardened concretes are not available at the present time to provide a further check on possible conclusions, but the indicated trends are explored here.

In the Bureau of Reclamation work [22] some mixtures were prepared with NaOH added. It was known that Na^+ and K^+ ions had a depressing effect on calcium in solution, and it was therefore postulated that sodium would have an adverse effect on the action of air-entraining agents which produced a film composed of the calcium salt of the surface active constituent of the agent. The

result of the addition was that $\bar{L}$ increased and α decreased compared to those obtained with similar mixes with the same w/c ratio and without the added alkali. In Mielenz' slurries the total air content measured by the air meter remained constant when the alkali was added, while in our data, air content consistently increased with increased alkali. This could be explained by the hypothesis that in the neat cement mixture the large voids present and produced by coalescence of smaller ones could escape more easily, while in concrete mixtures, the large voids tend more to be retained by adhesion to or entrapment in the aggregate particles. Thus the negative association between durability factor and alkalis shown in our concrete data in spite of the positive association between air content and alkali, could be explained by the hypothesis that dissolution of small bubbles and growth of the large ones took place.

7.3. Saturation Ratio

Explanations of the negative associations of saturation ratios with the alkalis are more doubtful. It seems reasonable to assume that if alkalis have some effect on the size, closeness together, and possible interconnections of the air voids in the concrete, they would also have some effect on the rate at and extent to which the concrete could soak up water. However, the fact that coefficients for the alkalis are negative in equations in which the saturation ratio is the independent variable while they are positive in relation to air content could be largely due to the circumstance that air content is a factor in the denominator of the formula for calculating saturation ratio.

7.4. Water-Cement Ratio

Water-cement ratio is another factor which is shown by Mielenz to have an effect on the rate of dissolution of small voids and thus on spacing factor, specific surface, and durability [23, 24]. Increased water/cement ratio tends to increase the fluidity of the mixture, thus aiding the dissolution of small bubbles and decreasing frost resistance. Comparisons between equations in table 11–33 and 11–35 for constant w/c concretes with corresponding ones in tables 11–34 and 11–36 where w/c varied, are somewhat inconclusive, but there are some differences which may be of interest. For instance, comparing eqs 4 in tables 11–35 and 11–36, shows that for all of the independent variables except one, the coef./s.d. ratios in table 11–35 are larger than those in table 11–36. This would indicate that permitting the w/c to vary increased the variation in durability factor and thus reduced the significance of the other variables in the equation when this extra variation was not accounted for. In order to check this further, some additional equations, not presented here, were calculated using w/c ratio of the A-series concretes as a dependent variable with the following results: Water-cement ratio (at constant slump)

a. had a negative relationship to air content;
b. had a positive relationship to saturation ratio;
c. had a negative relationship with durability factor when all cements were included, but was not significant when the air-entraining cements were excluded.

As Dr. Mielenz observed in a private communication, item c above "is extremely important since it shows the significance of w/c even when concrete is purposefully air-entrained. One explanation is the decreasing value of alpha as w/c increases."

7.5. Slump

According to Mielenz [25] decreased slump decreases average void size. Additional equations calculated from our data using the slump of the constant w/c ratio concretes indicated the following:

Slump (at constant w/c ratio):

a. had a positive relationship with air content;
b. had a negative relationship with saturation ratio when all cements were included, but was not significant when air-entraining cements were included;
c. had a positive relationship with durability factor.

The picture here is somewhat confused. Mielenz' tests showed that the effect of slump on durability factor was different with different types of air-entraining agents [26]. With our data, there is no information as to what kind of substance, if any, was acting as an air-entraining agent in the non-air-entraining cements, nor even what types were present in the air-entraining cements. As Mielenz pointed out in the private communication mentioned above, "the correlations that are forthcoming from my tests (Series II in ref. [23]) are not subject to the same interpretation as are your data because my tests compare the effect of slump on given cement-AEA combinations whereas yours evaluate the effect of slump on concretes containing diverse cements, the variation in slump occurring at constant w/c. In other words, the concretes developing high slump in your tests contain cements of proportionately lower water requirement, in part because they are air entraining."

In spite of the complications, in view of all the evidence, it seems reasonable to suspect that whatever effect slump has on air content and durability may be largely due to an effect of some kind on the character of the air void system.

7.6. Setting Time

The last variable for which there is any basis for comparing our findings with those of Mielenz is setting time. He points out that anything that prolongs the time of setting increases the time available for dissolution of smaller bubbles before hardening takes place, and therefore results in lower specific surface and higher spacing factor [27]. Mielenz' work was done on neat cement mixtures with retarders added to prolong setting time, whereas in our tests on concretes, only the results of normal variation in setting time of the cements were available. No tests of setting time of the concretes were made. However, additional equations calculated with setting time of the cements as an independent variable produced the following results:

a. both initial and final set had a significant positive relationship with air content when all cements were included, but not when the air-entraining cements were excluded;

b. both initial and final set had a significant positive relationship to saturation ratio with only non-air-entraining cements; and final set had a significant positive relationship when all air-entraining cements were included;

c. both initial and final set had significant positive relationships with durability factor when saturation ratio was also included as an independent variable, both with all cements and with air-entraining cements excluded.

Mielenz had the following to say on these results, "The correlation involving setting time of the cements indicates that this property influences the various qualities of the concrete directly or indirectly. A time-of-setting test on the matrix of concrete would be more meaningful. Your correlation of set with air content (a, above) suggests that air content of AE concrete increases with setting time of air-entraining cement, but possibly the relationship is due to a tendency of the AE addition to increase setting time of the cement, rather than through any direct action of setting time on the air content of concrete."

So far as the remaining independent variables in the equations in tables 11–33, 11–34, 11–35, and 11–36 are concerned, we are not aware of any other work with which our results might be compared. Air permeability fineness appears to have a negative association with durability factor for the non-air-entraining cements only when air content is also included as an independent variable. MgO also shows significant negative association with durability factor when air content is included, both with and without the air-entraining cements. Of the trace elements the only one which shows a consistent significant relationship with

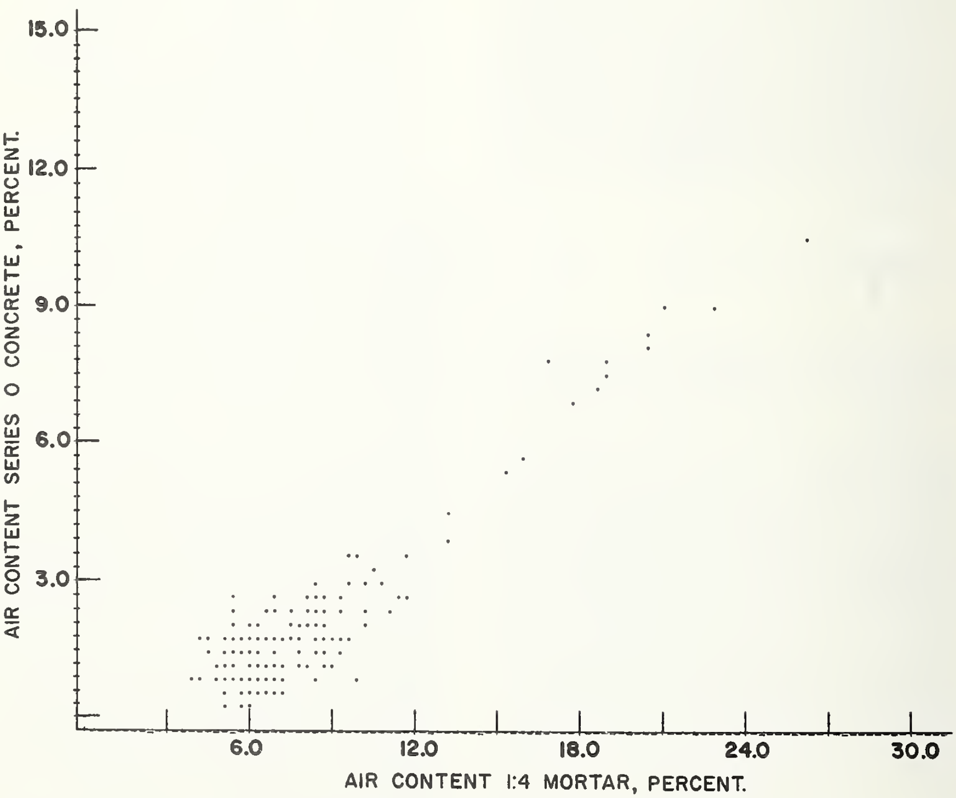

FIGURE 1. *Results of plotting the air content of Series O concretes made with AE + NAE cements versus the air content of 1:4 (cement to 20–30 Ottawa sand) mortars.*

durability factor is rubidium. This association is most consistent when saturation ratio is included as an independent variable.

When one considers the small amounts in which rubidium and other trace elements are present in the cement, it seems unreasonable that they should have an effect on such a gross property of the concretes in which the cements are incorporated as the number of cycles of freezing-and-thawing the concrete specimens can withstand. If Rb, for instance, does have a real effect, it seems that it would probably come about by means of some such mechanism as an effect on the most finely divided portion of air void system such as those shown by Mielenz and his colleagues. Effects of some of the trace elements should be investigated directly with neat cement mixtures using similar techniques.

It is interesting to note that for all the independent variables except air content in eqs 4, 5, 6, and 7 in tables 11–33 through 11–36 that have coef./s.d. ratios greater than 1.0, the coefficients are negative. This tends to indicate that, if the hypothesis that the effect on durability is due to an effect on the films protecting the small air voids is valid, most of the minor ingredients that have an effect have an adverse effect on the air void system.

7.7. Air Content of Test Mortars Versus Air Content of Concretes

The relationship between the air in the Series O concrete (made with a w/c of 0.635) and the air in the standard 1:4 (cement to 20–30 Ottawa sand) mortar is presented in figure 1. This graph is a plot of the values of both the AE and the NAE cements. Some of the plotted points represent more than one value because of the limitations of the computer printer when used as a plotter. A corresponding plot of the air contents of Series A concretes (5 ± 1-in slump) versus the air content of the 1:4 mortars, both made of AE + NAE cements, is presented in figure 2. In both figures 1 and 2, the cements having high air content in the 1:4 mortar also had high air content in the concrete. The Series O concretes appeared to have a smaller dispersion of values.

Using different scales, plots were also made of the relationships of air in concrete and air in mortar made of the NAE cements. These plots are presented in figures 3 and 4 for the Series O and A concretes respectively.

The equations calculated for the relationships between the air content of the 1:4 (cement to 20–30 Ottawa sand) mortars (SAIR) and the air

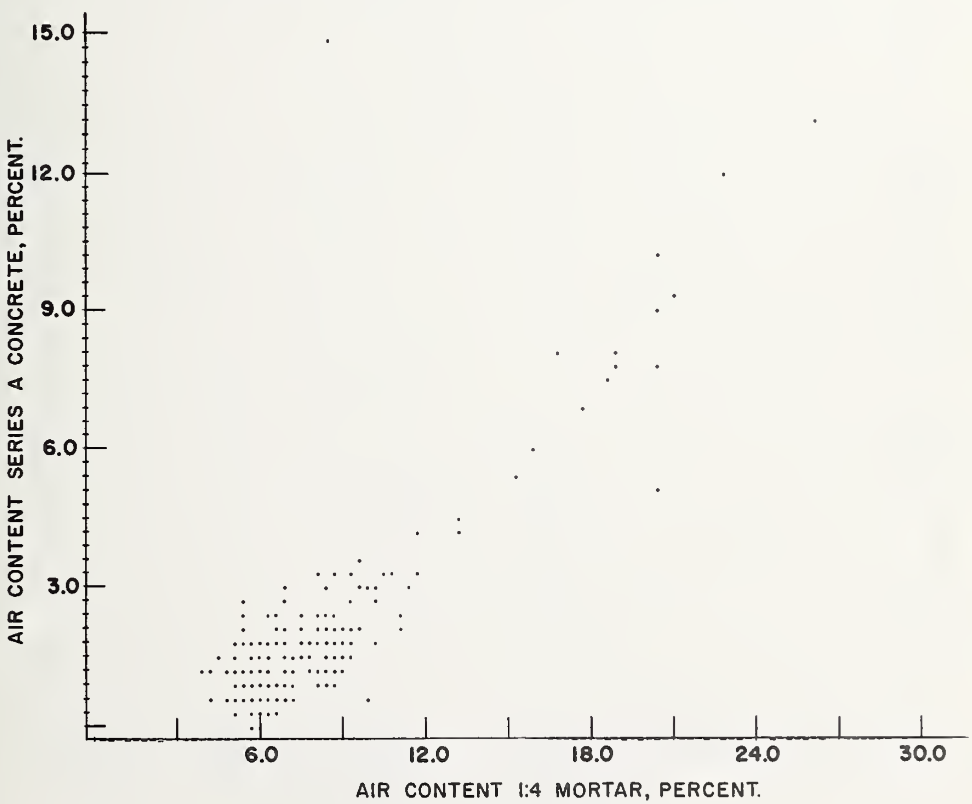

FIGURE 2. *Results of plotting the air content of Series A concretes made with AE + NAE cements versus the air content of 1:4 (cement to 20–30 Ottawa sand) mortars.*

content of the Series O and A concretes made of AE + NAE, and the NAE cements are presented in table 11–37. The reduction of variance ("F" values) was, in each equation, highly significant. However, when the AE cements were included as in eqs 1 and 2 the "F" values were about 10 times those of eqs 3 and 4 where only the NAE cements were included.

TABLE 11–37. *Relationship of air-contents of concretes OAIR and AAIR, and the air-contents of 1:4 (cement to 20–30 Ottawa sand) mortars, SAIR*

Equation No.	Figure No.	Cement type		"F"	D.F.	Critical F
1	1	AE+NAE	OAIR = −1.604 + 0.455 SAIR s.d. = (0.114) (0.013)	638	2:189	3.05
2	2	AE+NAE	AAIR = −2.103 + 0.560 SAIR s.d. = (0.145) (0.016)	488	2:189	3.05
3	3	NAE	OAIR = −0.388 + 0.274 SAIR s.d. = (0.178) (0.024)	66	2:175	3.05
4	4	NAE	AAIR = −0.703 + 0.307 SAIR s.d. = (0.214) (0.029)	57	2:175	3.05

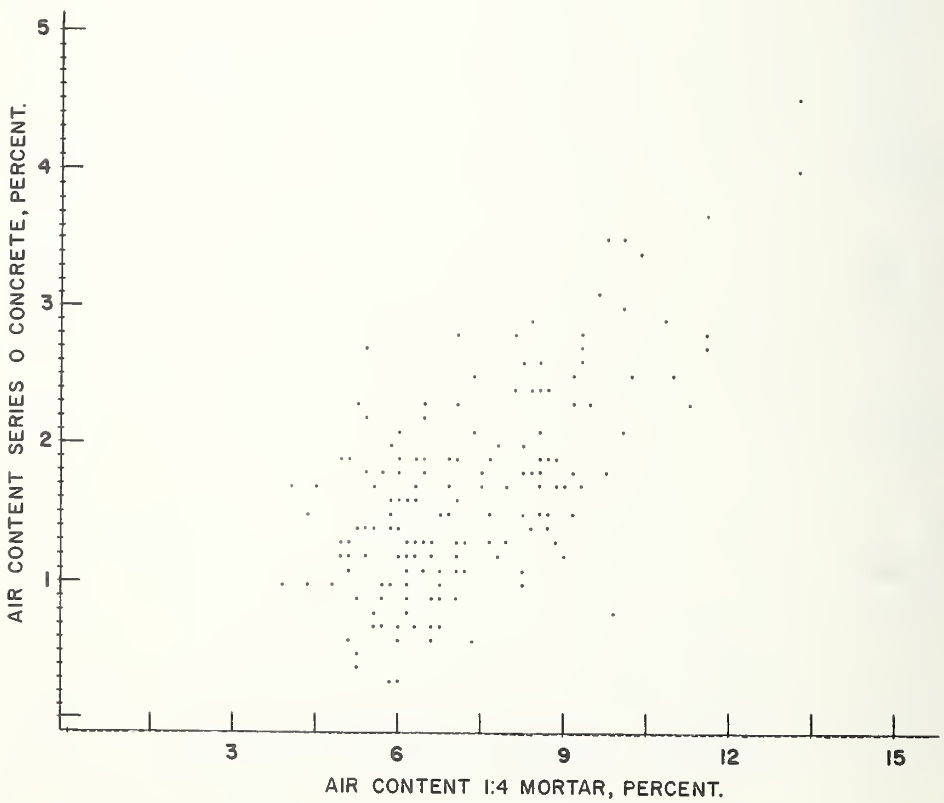

FIGURE 3. *Results of plotting the air content of Series O concretes made with NAE cements versus the air content of 1:4 (cement to 20–30 Ottawa sand) mortars.*

8. Summary and Conclusions

8.1. Laboratory freezing-and-thawing tests were conducted on concretes made of 199 portland cements of different types and from different sources. One series of concretes was made using a water/cement ratio of 0.635 and the other series with the quantity of water adjusted to give a 5 ± 1-in slump. A nominal quantity of 5.5 bags of cement per cubic yard was used. The 3- × 4- × 16-in specimens were moist cured for 14 days then air dried for 28 days after which the rapid (2 hr) cycles of freezing and thawing in water were started. The durability factor was calculated from the relative dynamic Youngs' modulus of elasticity, on the basis of 40-percent reduction or 300 cycles depending on which occurred first. The freezing-and-thawing cycles were continued until a 40-percent reduction in modulus was attained with all specimens. The specimens were then placed in a fog room for different periods and determinations made of the increase in fundamental resonant frequency in order to determine the extent of autogenous healing.

8.2. The saturation ratio or amount of water absorbed in 24 hours divided by the possible absorption ranged from 0.20 to more than 0.80.

8.3. The durability factor for the concretes which had been dried in laboratory air for 28 days following moist air curing for 14 days ranged from about 5 to 95 when frozen and thawed in water.

8.4. The concretes made with non-air-entraining cements withstood from 10 to about 300 cycles of freezing and thawing before the dynamic modulus was reduced to 60 percent of that at the start of the tests. The average number of cycles was about 100. The concretes made of the air-entraining cements required about 300 to 900 cycles of freezing and thawing for a reduction of 40 percent in dynamic modulus.

8.5. At the time the concrete specimens had attained a 40-percent reduction in dynamic modulus there was a weight loss ranging up to 22 percent. A few specimens which failed very early had a slight weight gain.

8.6. After the freezing-and-thawing tests had been continued until there was a 40-percent loss of dynamic modulus the concrete specimens were stored in a fog room and retested after 1, 2, 3, 4, or 5 years. The non-air-entrained concretes generally regained their original dynamic modulus or more, but the air-entrained specimens did not gain as much. All of the regain of dynamic modulus took place in 16 months or less. There were significant differences between cements in amount of autogenous healing.

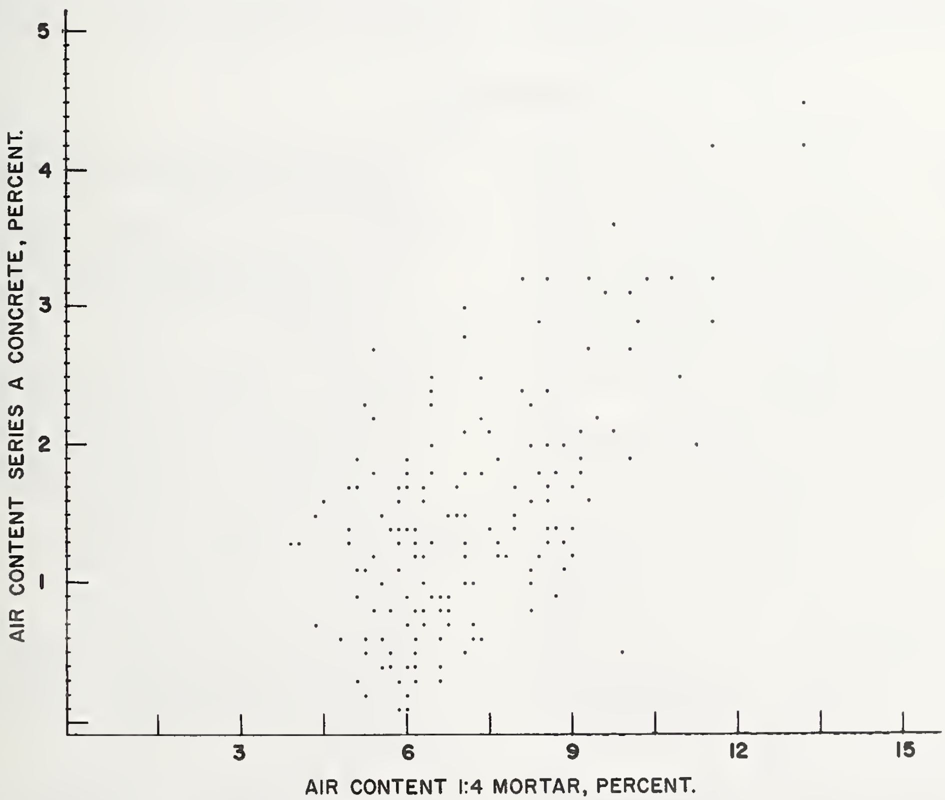

FIGURE 4. *Results of plotting the air content of Series A concretes made with NAE cements versus the air content of 1:4 (cement to 20–30 Ottawa sand) mortars.*

8.7. Computations of multivariable equations by a least-squares method were used to determine the chemical and physical properties associated with the durability factor, weight-loss at 40-percent reduction of dynamic modulus, and saturation ratio. The equations were computed for concretes made from all cements for which minor constituents and trace elements had been determined. The equations were computed using as independent variables either the major potential compounds or the major oxides, each with other commonly determined variables, and these with trace elements found to be significant.

The following observations relate to equations as summarized in tables 11–31 and 11–32 for concretes made of AE + NAE cements using a water/cement ratio of 0.635 and concretes made having a slump of 5 $\pm$ 1 in.

8.7.1. The durability factor was primarily dependent on the air content of the concretes. Increases in C_2S, K_2O, MgO and possibly Cu, Rb, Ti and fineness were associated with decreases of the durability factor.

8.7.2. An increase of the air content was associated with an increase of the weight-loss at the time of 40-percent reduction of dynamic modulus. Increases of C_3A and C_4AF were also associated with increases of the weight-loss. Increases in K_2O and possibly Na_2O, Pb, Rb, and Ti were associated with decreases of the weight-loss.

8.7.3. An increase of the air-content was associated with a decrease of the saturation ratio. An increase of the C_2S, C_4AF and possibly MgO, loss on ignition, Rb, Ni, Co, and Cu were associated with an increase of the saturation ratio.

8.8. Computations of multivariable equations for the concretes made with non-air-entraining cements were in general agreement with those calculated with all the cements. The coefficients for the air content of the concretes were generally not so highly significant as when the air-entraining cements were included but they were generally significant.

8.9. Computations made using the principal oxides together with other commonly determined variables, or these with minor constituents and trace elements resulted in equations with nearly the same estimated standard deviation values as when the calculated major potential compounds were used as independent variables.

8.10. The coefficients for the individual trace elements were generally not highly significant when used in multivariable equations for some of the dependent variables and their use did not always result in a significantly better fit, i.e., a significantly lower estimated standard deviation.

8.11. There was a good correlation between the air entrained in the concrete and that entrained in the standard 1:4 (cement to 20–30 Ottawa sand) mortar.

8.12. There was evidence that some of the variables such as alkali, water/cement ratio, slump, and possibly setting time, might have influenced durability through an effect on the air-void system, particularly the small air voids, as reported by Mielenz and others.

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Section 12. Water-Loss and Absorption of Concrete

R. L. Blaine and H. T. Arni

The relationships between portland cement characteristics and the loss of weight on drying in air for 56 days and the absorption with subsequent 28 days storage in water of concretes were studied by computing multivariable regression equations with the aid of a digital computer. The percentage absorption on rewetting was significantly related to the weight loss of concretes when air dried. The composition of the cement and the air-content of the concretes were also found to be related to the weight-loss and absorption as well as to ratios of weight-gain/weight-loss. The effects of trace elements in the cements were generally of doubtful significance in the drying and absorption tests.

Key words: Absorption; cement composition; concrete; loss on drying; portland cement; trace elements.

Contents

1. Introduction

The resistance of concrete to attack by salts and other chemical reagents is dependent to some extent on the quality of the concrete. Thus, a concrete made with a high water/cement ratio is more subject to attack than one made of the same cement with a low water/cement ratio. Also, a concrete made with an adequate cement content is more resistant than a leaner concrete. The degree of hydration at the time of exposure to destructive reagents can also be a factor. The porosity and permeability of concrete may be associated with all of these variables.

The amount of an aggressive solution which can be absorbed is dependent to some extent on the amount of water that is removed on drying.

Lea and Desch [1][1] have indicated that the weight loss as a result of drying and the weight gain with subsequent rewetting are dependent on conditions of testing, such as temperature and time of drying and rewetting. In this study the specimens were dried under standard laboratory conditions, and the effects of different temperatures, humidities, and drying times were not investigated.

[1] Figures in brackets refer to literature references at the end of this section (p. 68).

2. Materials

2.1. Cements

The portland cements used in this study have previously been described [2,3,4]. They consisted of 199 commercially manufactured cements of different types, and were obtained from different areas of the USA, plus a few from other countries. These cements were classified primarily on the basis of their chemical analyses and physical tests.[2] The chemical analyses and other tests indicated a fairly broad range of properties.

2.2. Aggregates

The aggregates were, as indicated previously, [2] a high quality rounded quartzite coarse aggregate (White Marsh) and a sand from the same source. The fineness modulus for the sand was 2.82, for the coarse aggregate, 6.82, and for the combined aggregates 4.82.

2.3. Concrete

The procedures used in mixing and preparing the 6- × 8- × 16-in concrete specimens have previously been described in part 1, section 1 [2] as well as in part 4, section 10 [5]. Two series of concretes both with a nominal cement content of 5½ bags per cubic yard, were prepared. In one series a constant water/cement ratio (w/c) of 0.635 was used. These concretes are referred to as the Series O concretes. In the other series the w/c was adjusted, if necessary, to obtain a 5 ± 1-in slump. These concretes are referred to as Series A concretes.

3. Tests and Nomenclature

The 6- × 8- × 16-in (approximately 15- × 20- × 40-cm) concrete specimens used for drying and absorption tests were the same as those used for the volume change measurements reported in part 4 section 10 [5]. After casting, the specimens were: (1) cured under wet burlap for the first 20 to 24 hours, (2) stored in the fog room at 100-percent relative humidity until they were 14 days old, (3) placed in laboratory air at 73 ± 1 °F, and 50 ± 5-percent relative humidity for 56 days, and (4) immersed in water at 73 °F for an additional 28 days. Measurements were made of the weights of the specimens at 24 hours, at 14 days, after air-drying for 28 and 56 days, and after storage in water for 28 days. Companion 3- × 4- × 16-in beams made from the same concretes were given the same treatment.

The percentage weight-loss of the specimens as a result of drying in laboratory air was calculated from the ratio of the weight after the period of air drying to the weight after removal from the fog room at 14 days. This percentage is referred to as ODRY and ADRY for the Series O and A concretes, respectively. The percentage gain of weight when the air-dried specimens were placed in water was calculated from the ratio of the weight after water storage to the weight after air storage. This percentage is referred to as OWET and AWET for the Series O and A concretes respectively.

Various other notations are used for the various ratios and differences of the percentage weight-loss and percentage absorption. These are as follows:

ORWT and ARWT are used to designate the ratios of OWET/ODRY and AWET/ADRY. OWTR and AWTR are used to designate the ratios (ODRY-OWET)/ODRY and (ADRY-AWET)/ADRY respectively.

The air contents of the concretes are sometimes referred to as such and at times by OAIR and AAIR for the two series. The values were based on the percentage air by volume determined gravimetrically according to ASTM Designation C 138, on the plastic concrete, as indicated in part 1 section 1 [2].

Other abbreviations and symbols are the same as those used in previous parts and sections of this series of articles.[3]

4. Statistical Studies

The statistical techniques used to determine and evaluate the independent variables associated with the percentage-loss of weight on drying, or percentage weight-gain with subsequent storage in water, or the various ratios and differences were the same as those described and used in previous parts and sections of this series of articles. Multivariable regression equations were calculated by the method of least-squares to evaluate the significance of the various independent variables associated with the dependent variables. Residuals of multivariable equations were fitted by a least-squares method to other independent variables and the reduction in variance calculated.

[2] Included were 82 Type I, 68 Type II, 20 Type III, 3 Type IV, and 12 Type V cements. Also included were 8 Type IA, 3 Type IIA, and 3 Type IIIA cements.

[3] Among the abbreviations or symbols used are C_3A, C_3S, C_2S, and C_4AF for the calculated potential compounds, tricalcium aluminate, tricalcium silicate, dicalcium silicate, and tetracalcium aluminoferrite, respectively. Also, used are AE + NAE for air-entraining plus non-air-entraining cements, NAE for non-air-entraining cements, APF for air permeability fineness, WAGN for Wagner turbidimeter fineness, Loss for loss on ignition, and Insol for insoluble residue.

If any of the additional independent variables indicated a significant reduction in variance, they were tried in the equation and retained if the coef./s.d. ratio was greater than 1.0.[4]

As in previous sections, comparisons were made of the degree of fit of equations using commonly determined variables as independent variables and these together with minor and trace elements. The level of significance of any reduction in the S.D. values resulting from the use in the equation of the additional independent variables was calculated for various pairs of equations or for an equation and the S.D. values of the property of the concrete (as presented in footnotes in the tables). The reduction in variance for the different pairs of equations and critical "F" values which must be equalled or exceeded for significance at the 5.0- and 1.0-percent significance levels are presented in a table summarizing these calculations.

Equations were calculated using both the calculated potential compounds as well as the major oxides, each together with other independent variables. Equations were calculated for both the AE + NAE cements and the NAE cements for all the dependent variables.

Equations were also computed for the "odds" and "evens" in the array of cements. If the coefficients and coef./s.d. ratios of these equations were in close agreement with those for the equation computed for all cements, confidence in the relationship was enhanced.

Although the drying and absorption tests were made on concretes made with each of the cements, the calculations of the equations presented in this section were limited to those for which trace elements had been determined. The concretes made with the three white cements and the one having a high autoclave expansion were excluded, as were a few others that had large deviations from the calculated relationship for no apparent reason. The frequency distributions of the various properties as well as calculated contributions to the various independent variables included all the concretes for which values were available.

Equations presented in this article were selected from a large number of trial equations indicating the relationship of various independent variables to percentage weight loss or gain, or the differences and ratios. The differences and trends indicated by these series of equations will be treated in subsection 6. Some of the limitations on interpretations of multivariable regression equations, as well as the other statistical techniques used, have been discussed in part 1 section 1, subsections 4.2, 4.3, and 5 [2] as well as in most of the preceding sections of this series of articles.

Table 12–1. *Frequency distribution of cements with respect to ODRY, the percentage weight loss of Series O concretes when air-dried for 56 days*

Type cement	Percentage weight loss													
	1.8 to 2.0	2.0 to 2.2	2.2 to 2.4	2.4 to 2.6	2.6 to 2.8	2.8 to 3.0	3.0 to 3.2	3.2 to 3.4	3.4 to 3.6	3.6 to 3.8	3.8 to 4.0	4.0 to 4.2	4.2 to 4.4	Total
	Number of cements													
I	1	8	16	19	23	7	6	2						82
IA					2	3	3							8
II		2	10	17	15	8	8	1	5	2				68
IIA				1	1				1					3
III	4	6	5	3	2									20
IIIA			3											3
IV, V			1	1	1	3	3		4		1		1	15
Total	5	16	35	41	44	21	20	3	10	2	1	0	1	199

5. Results of Tests

5.1. Loss of Weight as a Result of Drying

5.1.1. Weight-Loss of Series O Concretes

The frequency distribution of percentage weight-loss during drying of the Series O concretes is presented in table 12–1. The values ranged from less than 2.0 percent to more than 4.2 percent and there was an overlapping of the values for the different types of cement.

Equations relating the variables associated with the loss of weight of Series O concretes made with AE + NAE cements are presented in table 12–2. As indicated in eq 1, an increase in C_3S was associated with a decrease of the weight-loss and an increase in C_4AF with an increase of the weight-loss. The reduction in variance was highly significant.[5]

[4] Statistical terms and notations employed in this section are the same as those in previous sections. For example, S.D. refers to the estimated standard deviation calculated from the residuals of a fitted equation, or the estimated standard deviation about the average. Also, s.d. refers to the estimated standard deviation of a coefficient of an independent variable used in a fitted equation, coef./s.d. the ratio of the magnitude of an estimated coefficient (of an independent variable used in an equation) to its estimated standard deviation, and "F" equals Fisher's ratio of variances.

[5] The reduction in variance or "F" ratios of comparable S.D. values are presented in table 12–33 together with the critical "F" ratios which must be equaled or exceeded for significance at the $\alpha = 0.01$ and $\alpha = 0.05$ probability levels. Eq 0 as used in table 12–33 refers to the S.D. value of the corresponding dependent variable as given in footnotes in the tables of equations.

TABLE 12–2. *Coefficients for equations for AE + NAE cements relating the percentage loss of weight when dried for 56 days in laboratory air after 14 days of moist curing of concretes of nominal 5 ½ bags cement per cubic yard and a water-cement ratio of 0.635 to various independent variables (ODRY)*

Eq. No.	Note		Const.	C_3S	C_4AF	Al_2O_3	Fe_2O_3	Na_2O	K_2O	SO_3	Loss	Air content	Ba	Cu	Rb	Zr	S.D.
1	1	ODRY	= +3.249	−0.02023	+0.04204	---	---	---	---	---	---	---	---	---	---	---	0.3440
		s.d.	= (0.253)	(0.00397)	(0.01168)	---	---	---	---	---	---	---	---	---	---	---	---
2	1	ODRY	= +4.256	−0.02259	+0.03600	---	---	−0.5737	−0.6832	−0.2418	−0.0692	+0.0681	---	---	---	---	0.2678
		s.d.	= (0.237)	(0.00327)	(0.00941)	---	---	(0.1245)	(0.0978)	(0.0653)	(0.0403)	(0.0119)	---	---	---	---	---
3	1	ODRY	= +4.242	−0.02268	+0.03219	---	---	−0.5326	−0.5940	−0.2490	−0.0654	+0.0647	+1.012	+2.702	−16.13	−0.5733	0.2649
		s.d.	= (0.237)	(0.00324)	(0.00973)	---	---	(0.1259)	(0.1121)	(0.0653)	(0.0406)	(0.0119)	(0.604)	(2.491)	(11.91)	(0.5150)	---
3A	2	ODRY (odd)	= +4.479	−0.02019	+0.01549	---	---	−0.5368	−0.5920	−0.3590	−0.0857	+0.0728	*+0.763	+5.566	*+3.44	−3.1321	0.2687
		s.d.	= (0.340)	(0.00442)	(0.01478)	---	---	(0.1664)	(0.1672)	(0.0950)	(0.0638)	(0.0172)	(1.156)	(3.672)	(16.13)	(1.3896)	---
3B	2	ODRY (even)	= +4.135	−0.02620	+0.04592	---	---	−0.4597	−0.5782	−0.1636	*−0.0357	+0.0519	+1.159	*+0.540	−44.20	*−0.2441	0.2534
		s.d.	= (0.345)	(0.00505)	(0.01340)	---	---	(0.2243)	(0.1709)	(0.0926)	(0.0529)	(0.0165)	(0.749)	(3.574)	(18.25)	(0.5540)	---
				CaO	SiO_2												
4	1	ODRY	= −1.671	−0.0342	+0.2320	+0.1747	+0.1763	---	---	---	---	---	---	---	---	---	0.3240
		s.d.	= (1.696)	(0.0224)	(0.0337)	(0.0435)	(0.0355)	---	---	---	---	---	---	---	---	---	---
5	1	ODRY	= +4.994	−0.1003	+0.1615	+0.1778	+0.1408	−0.6087	−0.7604	−0.2111	−0.0765	+0.0680	---	---	---	---	0.2674
		s.d.	= (1.933)	(0.0217)	(0.0354)	(0.0402)	(0.0325)	(0.1263)	(0.1143)	(0.0728)	(0.0444)	(0.0119)	---	---	---	---	---
6	1	ODRY	= +5.815	−0.1090	+0.1497	+0.1840	+0.1211	−0.6032	−0.6818	−0.2309	−0.0889	+0.0637	+1.426	+3.385	−19.37	---	0.2622
		s.d.	= (1.935)	(0.0215)	(0.0354)	(0.0398)	(0.0338)	(0.1246)	(0.1226)	(0.0719)	(0.0438)	(0.0118)	(0.620)	(2.482)	(11.85)	---	---
6A	2	ODRY (odd)	= +6.547	−0.1013	+0.1124	+0.1794	+0.0750	−0.6142	−0.6597	−0.3691	−0.1163	+0.0743	*+0.725	+5.019	*−2.95	---	0.2696
		s.d.	= (2.986)	(0.0336)	(0.0495)	(0.0539)	(0.0510)	(0.1657)	(0.1818)	(0.1099)	(0.0650)	(0.0175)	(1.161)	(3.713)	(16.22)	---	---
6B	2	ODRY (even)	= +3 851	−0.1109	+0.2114	+0.2352	+0.1839	−0.5280	−0.6145	*−0.0996	*−0.0360	+0.0491	+1.488	*+1.534	−49.61	---	0.2520
		s.d.	= (2.670)	(0.0292)	(0.0573)	(0.0637)	(0.0462)	(0.2171)	(0.1772)	(0.1047)	(0.0616)	(0.0165)	(0.822)	(3.652)	(18.38)	---	---

Note 1, 180 cements, Avg. = 2.657, S.D. = 0.3908
Note 2, 90 cements
*Coef./s.d. ratio less than 1.0

TABLE 12–3. *Coefficients for equations for NAE cements relating the percentage loss of weight when dried for 56 days in laboratory air after 14 days moist curing of concretes of a nominal 5½ bags cement per cubic yard and a water-cement ratio of 0.635, to various independent variables (ODRY)*

Eq. No.	Note		Const.	C_3S	C_4AF	Al_2O_3	Fe_2O_3	Na_2O	K_2O	SO_3	Loss	Air content	Ba	Cu	Rb	Zr	S.D.
1	1	ODRY	= +3.093	−0.01847	+0.04758												0.3437
		s.d.	= (0.266)	(0.00412)	(0.01204)												
2	1	ODRY	= +4.234	−0.02247	+0.03530			−0.5931	−0.7147	−0.2425	−0.0606	+0.0886					0.2724
		s.d.	= (0.255)	(0.00346)	(0.00985)			(0.1309)	(0.1040)	(0.0678)	(0.0422)	(0.0307)					
3	1	ODRY	= +4.233	−0.02265	+0.03474			−0.5362	−0.6471	−0.2549	−0.0573	+0.0846	+0.923		−16.49	−0.657	0.2697
		s.d.	= (0.254)	(0.00343)	(0.00977)			(0.1328)	(0.1154)	(0.0678)	(0.0426)	(0.0310)	(0.625)		(12.46)	(0.528)	
3A	2	ODRY (odd)	= +4.193	−0.02259	+0.04342			−0.4595	−0.8450	−0.2356	* −0.0480	+0.0887	+1.265		* −9.07	−3.868	0.2842
		s.d.	= (0.366)	(0.00504)	(0.01568)			(0.1758)	(0.1841)	(0.0995)	(0.0793)	(0.0519)	(1.234)		(18.70)	(3.863)	
3B	2	ODRY (even)	= +4.246	−0.02278	+0.03085			−0.8014	−0.4687	−0.2629	−0.0810	+0.0987	+0.981		* −18.00	* −0.124	0.2634
		s.d.	= (0.395)	(0.00539)	(0.01357)			(0.2319)	(0.1675)	(0.1003)	(0.0548)	(0.0404)	(0.823)		(18.62)	(0.572)	
				CaO	SiO_2												
4	1	ODRY	= −2.941	* −0.0165	+0.2336	+0.1744	+0.2016										0.3179
		s.d.	= (1.724)	(0.0228)	(0.0344)	(0.0441)	(0.0361)										
5	1	ODRY	= +5.290	−0.1032	+0.1576	+0.1736	+0.1350	−0.6300	−0.8013	−0.2148	−0.0698	+0.0895					0.2721
		s.d.	= (2.012)	(0.0228)	(0.0371)	(0.0423)	(0.0340)	(0.1330)	(0.1222)	(0.0756)	(0.0464)	(0.0306)					
6	1	ODRY	= +5.841	−0.1089	+0.1496	+0.1819	+0.1184	−0.5881	−0.7230	−0.2404	−0.0729	+0.0756	+1.298	+3.014	−18.27	−0.554	0.2674
		s.d.	= (2.032)	(0.0227)	(0.0375)	(0.0421)	(0.0358)	(0.1338)	(0.1309)	(0.0752)	(0.0468)	(0.0316)	(0.646)	(2.623)	(12.46)	(0.528)	
6A	2	ODRY (odd)	= +8.432	−0.1290	+0.1000	+0.1688	+0.1136	−0.4617	−0.9274	−0.3016	* −0.0547	+0.0825	* +1.087	+8.770	* −16.66	* −3.204	0.2698
		s.d.	= (2.738)	(0.0324)	(0.0497)	(0.0555)	(0.0543)	(0.1698)	(0.1925)	(0.1093)	(0.0781)	(0.0515)	(1.180)	(4.010)	(18.23)	(3.726)	
6B	2	ODRY (even)	= +1.628	−0.0771	+0.2207	+0.2358	+0.1515	−0.8346	−0.4699	−0.1697	* −0.0531	+0.0973	+1.002	* −0.109	−20.33	* −0.148	0.2651
		s.d.	= (3.286)	(0.0340)	(0.0664)	(0.0710)	(0.0519)	(0.2497)	(0.1910)	(0.1182)	(0.0665)	(0.0422)	(0.950)	(3.708)	(18.85)	(0.595)	

Note 1, 168 cements, Avg. = 2.645, S.D. = 0.3920
Note 2, 84 cements
*Coef./s.d. ratio less than 1.0.

Other commonly determined variables, Na_2O, K_2O, SO_3, Loss, and air content of the concrete, also had coef./s.d. ratios greater than 1.0 (eq 2) and, resulted in a further highly significant reduction of variance. (See table 12–33, p 63).

The additional use of the trace elements Ba, Cu, Rb, and Zr in eq 3 resulted in a slightly lower S.D. value, but the reduction in variance was not significant at the $\alpha = 0.05$ level. (See table 12–33.) The coefficients for the four trace elements as well as loss on ignition were not highly significant, and when equations 3A and 3B were calculated for the "odds" and "evens" in the array of cements, the coef./s.d. ratio was less than 1.0 for each of these variables.[6]

Equation 4 was calculated using the major oxides instead of the potential compounds as in eq 1. There was a highly significant reduction in the S.D. value, and with the use of other commonly determined variables in eq 5 a further significant reduction in variance was attained. (See table 12–33) The additional use of the trace elements Ba, Cu, and Rb in eq 6 resulted in a slightly lower S.D. value with a reduction of variance significant at the $\alpha = 0.05$ level.

In eqs 6A and 6B calculated for the "odds" and "evens," SO_3, Loss, and the trace elements had coef./s.d. ratios of less than 1.0 in one or the other of the smaller groups of cements.

A similar series of equations calculated for the Series O concretes made with the NAE cements is presented in table 12–3. The use of the variables C_3S and C_4AF in eq 1, or these together with Na_2O, K_2O, SO_3, Loss, and air content in eq 2, each resulted in a highly significant reduction in variance. (See table 12–33.) The additional use of the trace elements Ba, Rb, and Zr in eq 3 did not result in a significant reduction of variance.

[6] If a number of cements having higher than normal values for an independent variable are included in one of the two groups (the "odds" or "evens") by the arbitrary division of the cements, this distribution may result in spurious coefficients for the variable. The estimated standard deviations of the coefficients for the smaller groups were usually larger than when a combination of the "odds" and "evens" in the array of cements was used in calculating the equation. If the coefficients of both "odds" and "evens" of an independent variable are significant, a greater confidence can be placed in the equation, and in the association of that independent variable with the dependent variable. If the coefficient for a variable in either the "odds" or "evens" is not greater than its s.d., some consideration may still be given to the larger groups of cements as indicating a possible relationship.

In eqs 3A and 3B calculated for the "odds" and "evens" in the array of cements, the coef./s.d. ratios for Loss, Rb, and Zr were less than 1.0 in one or both of the smaller groups.

The coef./s.d. ratio for CaO was less than 1.0 in eq 4 which was calculated using the major oxides. The coefficient for this variable was, however, highly significant in eqs 5 and 6 where other variables were also included. The use of the variables in eq 4 or these together with the additional variables in eq 5 resulted in a highly significant reduction in variance. (See table 12–33.)

The use of the trace elements Ba, Cu, Rb, and Zr in eq 6 did not result in a reduction of the S.D. value significant at the $\alpha = 0.05$ level. Also, the coef./s.d. ratios of the trace elements were less than 1.0 in one or both of the equations 6A and 6B calculated for the "odds" and "evens" in the array of cements. The loss on ignition of the cements also had a coef./s.d. ratio less than 1.0 with the smaller groups.

The calculated contributions of the independent variables to the percentage weight loss resulting from drying are presented in table 12–4 together with the calculated ranges of these contributions. These contributions and ranges were calculated from the coefficients of the independent variables in an equation and the approximate ranges of these variables in the cements of this investigation. These calculated values are estimates based

TABLE 12–4. *Calculated contributions of independent variables to ODRY, the percentage loss of weight resulting from air-drying of Series O concretes made of AE + NAE cements*

Independent variables	Ranges of variables (percent)	Coefficients from eq 3 table 12–2	Calculated contributions to ODRY	Calculated range of contributions to ODRY
			Const. = +4.24	
C_3S	20 to 65	−0.02268	−0.45 to −1.47	1.02
C_4AF	1 to 16	+0.03219	+0.03 to +0.51	0.48
Na_2O	0 to 0.7	−0.5326	0 to −0.37	0.37
K_2O	0 to 1.1	−0.594	0 to −0.65	0.65
SO_3	1.2 to 3.0	−0.249	−0.30 to −0.75	0.45
Loss*	0.3 to 3.3	−0.0654	−0.02 to −0.22	0.20
Air-content	0 to 11	+0.0647	0 to +0.71	0.71
Ba*	0 to 0.2	+1.012	0 to +0.20	0.20
Cu*	0 to 0.05	+2.702	0 to +0.14	0.14
Rb*	0 to 0.01	−16.13	0 to −0.16	0.16
Zr*	0 to 0.5	−0.573	0 to −0.29	0.29

*Coefficient of doubtful significance as coef./s.d. ratio was less than 2.0.

TABLE 12–5. *Frequency distribution of cements with respect to ADRY, the percentage weight loss of Series A concretes when air-dried for 56 days*

Type cement	Percentage weight loss													
	1.8 to 2.0	2.0 to 2.2	2.2 to 2.4	2.4 to 2.6	2.6 to 2.8	2.8 to 3.0	3.0 to 3.2	3.2 to 3.4	3.4 to 3.6	3.6 to 3.8	3.8 to 4.0	4.0 to 4.2	4.2 to 4.4	Total
	Number of cements													
I	2	6	6	22	19	12	5	5	2					79
IA			2	5	1									8
II	1		8	21	11	9	8	3		6				67
IIA			1		1	1								3
III	2	3	7	6	1		1							20
IIIA	1	2												3
IV, V			1	1	1	5	1	4	1				1	15
Total	6	11	25	55	34	27	15	12	3	6	0	0	1	195

TABLE 12–6. *Coefficients for equations for AE + NAE cements relating the percentage loss in weight when dried for 56 days in laboratory air after 14 days moist curing of concretes of a nominal 5 ½ bags cement per cubic yard and a 5 ± 1 inch slump, to various independent variables (ADRY)*

Eq. No.	Note		Const.	C_3A	C_3S	C_4AF		Na_2O	K_2O	SO_3	Loss	w/c	Air content	Ba	Cu	Rb	Zr	S.D.
1	1	ADRY	= +3.159	* −0.00741	−0.01636	+0.03991												0.3479
		s.d.	= (0.310)	(0.01012)	(0.00404)	(0.01443)												
2	1	ADRY	= +3.822	+0.03569	−0.02106	+0.05342		−0.6280	−0.8476	−0.1527	−0.0934							0.2755
		s.d.	= (0.260)	(0.00918)	(0.00338)	(0.01155)		(0.1292)	(0.1062)	(0.0707)	(0.0422)							
3	1	ADRY	= −0.794	+0.01840	−0.02199	+0.05438		−0.6089	−0.7276	−0.2273	−0.0956	+7.474	+0.06046					0.2569
		s.d.	= (0.942)	(0.00918)	(0.00316)	(0.01100)		(0.1214)	(0.1032)	(0.0681)	(0.0394)	(1.463)	(0.01708)					
4	1	ADRY	= −0.970	+0.02320	−0.02210	+0.05241		−0.5794	−0.6528	−0.2455	−0.0898	+7.654	+0.05940	+1.119	+3.920	−14.56	−0.6198	0.2522
		s.d.	= (0.939)	(0.00920)	(0.00312)	(0.01112)		(0.1215)	(0.1121)	(0.0678)	(0.0394)	(1.450)	(0.01699)	(0.598)	(2.387)	(11.53)	(0.4930)	
				CaO	SiO_2	Al_2O_3	Fe_2O_3											
5	1	ADRY	= +4.584	−0.0927	+0.1505	+0.2263	+0.1259	−0.6342	−0.8671	−0.1014	−0.1004							0.2764
		s.d.	= (2.025)	(0.0225)	(0.0374)	(0.0424)	(0.0332)	(0.1304)	(0.1183)	(0.0771)	(0.0464)							
6	1	ADRY	= −0.394	−0.0933	+0.1625	+0.1915	+0.1624	−0.6119	−0.7372	−0.1684	−0.0993	+7.472	+0.0601					0.2578
		s.d.	= (2.164)	(0.0212)	(0.0350)	(0.0401)	(0.0328)	(0.1224)	(0.1137)	(0.0734)	(0.0434)	(1.470)	(0.0172)					
7	1	ADRY	= −0.305	−0.0937	+0.1638	+0.1981	+0.1477	−0.5987	−0.6695	−0.1743	−0.0929	+7.301	+0.0563		+3.999	−14.62	−0.6769	0.2550
		s.d.	= (2.159)	(0.0211)	(0.0350)	(0.0401)	(0.0342)	(0.1235)	(0.1219)	(0.0729)	(0.0439)	(1.457)	(0.0172)		(2.431)	(11.67)	(0.5000)	

Note 1, 176 cements, Avg. = 2.675, S.D. = 0.3863 *Coef./s.d. ratio less than 1.0.

TABLE 12–7. *Coefficients for equations for NAE cements relating the percentage loss of weight when dried for 56 days in laboratory air after 14 days of moist curing of concretes of nominal 5 ½ bags cement per cubic yard and a slump of 5 ± 1 inch, to various independent variables (ADRY)*

Eq. No.	Note		Const.	C_3A	C_3S	C_4AF	Fe_2O_3	Na_2O	K_2O	SO_3	Loss	w/c	Air content	Ba	Cu	Rb	Zr	S.D.
1	1	ADRY	= +3.109	* −0.00568	−0.01529	+0.03969												0.3506
		s.d.	= (0.323)	(0.01049)	(0.00422)	(0.01492)												
2	1	ADRY	= +3.795	+0.03583	−0.02071	+0.05180		−0.6204	−0.8764	−0.1347	−0.0870							0.2796
		s.d.	= (0.276)	(0.00955)	(0.00356)	(0.01202)		(0.1339)	(0.1111)	(0.0734)	(0.0441)							
3	1	ADRY	= −1.033	+0.01841	−0.02215	+0.05362		−0.6325	−0.7723	−0.2350	−0.0887	+7.874	+0.0797					0.2618
		s.d.	= (1.043)	(0.00964)	(0.00335)	(0.01146)		(0.1277)	(0.1097)	(0.0723)	(0.0414)	(1.634)	(0.0329)					
4	1	ADRY	= −1.069	+0.02282	−0.02216	+0.05101		−0.5857	−0.6948	−0.2511	−0.0824	+7.864	+0.0646	+1.043	+3.748	−12.31	−0.6953	0.2578
		s.d.	= (1.041)	(0.00967)	(0.00331)	(0.01170)		(0.1287)	(0.1192)	(0.0721)	(0.0416)	(1.625)	(0.0333)	(0.625)	(2.504)	(12.11)	(0.5087)	
				CaO	SiO_2	Al_2O_3												
5	1	ADRY	= +4.808	−0.0935	+0.1445	+0.2213	+0.1178	−0.6286	−0.9019	−0.0880	−0.0961							0.2805
		s.d.	= (2.118)	(0.0236)	(0.0392)	(0.0446)	(0.0350)	(0.1352)	(0.1234)	(0.0800)	(0.0482)							
6	1	ADRY	= −0.443	−0.0956	+0.1611	+0.1902	+0.1586	−0.6373	−0.7869	−0.1785	−0.0940	+7.873	+0.0793					0.2627
		s.d.	= (2.267)	(0.0221)	(0.0368)	(0.0423)	(0.0343)	(0.1289)	(0.1211)	(0.0777)	(0.0454)	(1.641)	(0.0330)					
7	1	ADRY	= −0.310	−0.0953	+0.1624	+0.1970	+0.1442	−0.6111	−0.7226	−0.1824	−0.0862	+7.566	+0.0689		+3.684	−12.89	−0.7372	0.2602
		s.d.	= (2.270)	(0.0220)	(0.0369)	(0.0424)	(0.0361)	(0.1304)	(0.1293)	(0.0772)	(0.0460)	(1.632)	(0.0335)		(2.542)	(12.22)	(0.5151)	

Note 1, 164 cements, Avg. = 2.695, S.D. = 0.3861
*Coef./s.d. ratio less than 1.0.

on a single equation, and somewhat different values would be obtained by use of other equations. Similar computations for calculated contributions to dependent variables have also been made from corresponding equations in order that the trends may be followed more easily.[7]

5.1.2. Weight-Loss of Series A Concretes

The frequency distribution of the weight loss during drying of the Series A concretes is presented in table 12–5. There was an overlapping of the values for the concretes made of the different types of cement and a broad distribution of values.

Equations relating the variables associated with the loss of weight of Series A concretes made with AE + NAE cements are presented in table 12–6. In eq 1 the coef./s.d. ratio for C_3A was less than 1.0 but in eq 2, where other commonly determined variables were included, the coefficient was highly significant. With water/cement ratio and air content included with the independent variables in eq 3, the coef./s.d. ratio for C_3A was lowered. The relationship of C_3A, SO_3, and K_2O to water requirements of Series A concretes was previously reported in eq 5, table 2–20 [2].

The use of C_3A, C_3S, and C_4AF as independent variables in eq 1; these plus Na_2O, K_2O, SO_3, and Loss in eq 2; and the further addition of w/c and air content in eq 3 resulted for each of the equations in a highly significant reduction in variance. (See table 12–33.) The additional use of the trace elements Ba, Cu, Rb, and Zr as independent variables in eq 4 resulted in a slightly lower S.D. value, and the reduction in variance was significant at the $\alpha = 0.05$ level.

Using the major oxides in eq 5 instead of the calculated potential compounds also resulted in a highly significant reduction in variance. The additional use of w/c and air content as independent variables in eq 6 resulted in a further reduction in the S.D. value. However, addition of the trace elements Cu, Rb, and Zr in eq 7 did not result in a significant reduction in variance. (See table 12–33.)

[7] Corresponding tables for equations calculated for AE + NAE cements, using the calculated potential compounds, other commonly determined variables, and trace elements having a coef./s.d. ratio greater than 1.0 will be presented for other dependent variables. Summary tables (tables 12–34 and 12–35) are also presented for greater ease in comparing similar equations for the NAE cements.

A similar series of equations for the Series A concretes made of NAE cements is presented in table 12–7. The coefficients and coef./s.d. ratios of the independent variables are in reasonable agreement with those of table 12–6 where the AE cements were included. One exception may be noted; the coef./s.d. ratio for the air content was lower when only the NAE cements were included as in table 12–7. The use of trace elements together with commonly determined variables did not result in a significant reduction in variance. (See table 12–33.)

Using the coefficients of the independent variables of eq 4, table 12–6, and their ranges of values, computations were made of the calculated contributions to the ADRY values as well as the calculated ranges of these contributions. These calculated values are presented in table 12–8.

TABLE 12–8. *Calculated contributions of independent variables to ADRY, the percentage loss of weight resulting from air-drying of Series A concretes made of AE + NAE cement*

Independent variables	Range of variables (percent)	Coefficients from eq 4 table 12–6	Calculated contributions to ADRY	Calculated range of contributions to ADRY
			Const. = −0.97	
C_3A	1 to 15	+0.0232	+0.02 to +0.34	0.32
C_3S	20 to 65	−0.0221	−0.44 to −1.43	0.99
C_4AF	1 to 16	+0.0524	+0.05 to +0.83	0.78
Na_2O	0 to 0.7	−0.5794	0 to −0.40	0.40
K_2O	0 to 1.1	−0.6528	0 to −0.78	0.78
SO_3	1.2 to 3.0	−0.2455	−0.29 to −0.74	0.45
Loss	0.3 to 3.3	−0.0898	−0.03 to −0.30	0.27
w/c	0.55 to 0.72	+7.654	+4.21 to +5.51	1.30
Air-content	0 to 13	+0.0594	0 to +0.77	0.77
Ba*	0 to 0.2	+1.119	0 to +0.22	0.22
Cu*	0 to 0.05	+3.92	0 to +0.20	0.20
Rb*	0 to 0.01	−14.56	0 to −0.15	0.15
Zr*	0 to 0.5	−0.62	0 to −0.31	0.31

*Coefficient of doubtful significance as coef./s.d. ratio was less than 2.0.

Increases in C_3A, C_4AF, w/c, and air content were associated with increases in values for weight-loss. Increases in C_3S, Na_2O, K_2O, SO_3, and loss were associated with decreases in the values for weight-loss. Variations of w/c, C_3S, C_4AF, K_2O, and air content had the highest values for the calculated range of contributions to the values for weight-loss.

TABLE 12–9. *Frequency distribution of cements with respect to OWET, the percentage weight gain of Series O concretes when air-dried specimens were placed in water for 28 days*

Type cement	Percentage weight gain											
	1.8 to 2.0	2.0 to 2.2	2.2 to 2.4	2.4 to 2.6	2.6 to 2.8	2.8 to 3.0	3.0 to 3.2	3.2 to 3.4	3.4 to 3.6	3.6 to 3.8	3.8 to 4.0	Total
	Number of cements											
I	2	13	24	26	9	4	4					82
IA					1	2	5					8
II	1	7	11	19	12	6	6	4	1	1		68
IIA					1	1			1			3
III	3	7	4	3	3							20
IIIA				2		1						3
IV, V			1	1	3	3	1	3	1	1	1	15
Total	6	27	40	51	28	17	16	7	3	2	1	199

TABLE 12–10. *Coefficients for equations for AE + NAE cements relating the percentage gain in weight when moist stored for 28 days following 56 days drying in laboratory air of concretes of a nominal 5 ½ bags cement per cubic yard and a water-cement ratio of 0.635, to various independent variables (OWET)*

Eq. No.	Note		Const.	Air content	C_3S	C_4AF	Al_2O_3	Fe_2O_3	Na_2O	K_2O	SO_3	Loss	Cu	Rb	Zr	Ba	ODRY	S.D.
1	1	OWET	= +0.140	------	------	------	------	------	------	------	------	------	------	------	------	------	+0.9082	0.1264
		s.d.	= (0.064)	------	------	------	------	------	------	------	------	------	------	------	------	------	(0.0241)	------
2	1	OWET	= +2.440	+0.05301	------	------	------	------	------	------	------	------	------	------	------	------	------	0.3660
		s.d.	= (0.042)	(0.01503)	------	------	------	------	------	------	------	------	------	------	------	------	------	------
3	1	OWET	= +2.742	+0.06488	−0.01592	+0.04757	------	------	------	------	------	------	------	------	------	------	------	0.3243
		s.d.	= (0.246)	(0.01368)	(0.00372)	(0.01128)	------	------	------	------	------	------	------	------	------	------	------	------
4	1	OWET	= +3.868	+0.10186	−0.01980	+0.03599	------	------	−0.7136	−0.7094	−0.1776	−0.0727	------	------	------	------	------	0.2451
		s.d.	= (0.214)	(0.01083)	(0.00296)	(0.00859)	------	------	(0.1138)	(0.0895)	(0.0594)	(0.0367)	------	------	------	------	------	------
5	1	OWET	= +3.843	+0.09755	−0.01967	+0.02997			−0.6705	−0.5972	−0.1830	−0.0669	+4.890	−18.50	−0.8074	+0.891	------	0.2375
		s.d.	= (0.210)	(0.01066)	(0.00287)	(0.00869)	------	------	(0.1128)	(0.1002)	(0.0583)	(0.0363)	(2.230)	(10.53)	(0.4618)	(0.541)	------	------
5A	2	OWET (odd)	= +3.828	+0.10766	−0.01688	+0.02126	------	------	−0.7603	−0.7861	−0.1649	−0.1006	+7.659	* +5.66	−2.5905	+2.407	------	0.2329
		s.d.	= (0.291)	(0.01490)	(0.00365)	(0.01227)	------	------	(0.1502)	(0.1406)	(0.0915)	(0.0506)	(3.219)	(14.12)	(1.1056)	(0.740)	------	------
5B	3	OWET (even)	= +3.931	+0.09227	−0.02516	+0.04072	------	------	−0.7181	−0.4260	−0.1831	* −0.0259	+4.881	−47.88	* −0.3411	* −0.151	------	0.2272
		s.d.	= (0.308)	(0.01476)	(0.00460)	(0.01213)	------	------	(0.1780)	(0.1488)	(0.0736)	(0.0511)	(3.168)	(15.93)	(0.5026)	(0.797)	------	------
					CaO	SiO_2												
6	1	OWET	= −2.037	+0.08143	* −0.01505	+0.1940	+0.1084	+0.1883	------	------	------	------	------	------	------	------	------	0.2985
		s.d.	= (1.608)	(0.01296)	(0.02105)	(0.0308)	(0.0399)	(0.0338)	------	------	------	------	------	------	------	------	------	------
7	1	OWET	= +5.713	+0.10070	−0.09772	+0.1268	+0.1167	+0.1225	−0.7317	−0.7647	−0.1484	−0.0906	------	------	------	------	------	0.2457
		s.d.	= (1.773)	(0.01092)	(0.01994)	(0.0322)	(0.0367)	(0.0299)	(0.1160)	(0.1049)	(0.0668)	(0.0406)	------	------	------	------	------	------
8	1	OWET	= +6.365	+0.09597	−0.10391	+0.1160	+0.1228	+0.0978	−0.7063	−0.6823	−0.1725	−0.0926	+5.427	−19.18	−0.7098	+1.156	------	0.2367
		s.d.	= (1.753)	(0.01068)	(0.01953)	(0.0317)	(0.0357)	(0.0306)	(0.1142)	(0.1106)	(0.0650)	(0.0402)	(2.244)	(10.57)	(0.4640)	(0.562)	------	------
8A	2	OWET (odd)	= +4.537	+0.10713	−0.07507	+0.1201	+0.0973	+0.0822	−0.7521	−0.7954	−0.1231	−0.1047	+7.684	* +6.26	−2.6118	+2.399	------	0.2356
		s.d.	= (2.800)	(0.01518)	(0.03084)	(0.0423)	(0.0516)	(0.0455)	(0.1568)	(0.1647)	(0.1076)	(0.0543)	(3.260)	(14.39)	(1.1275)	(0.764)	------	------
8B	3	OWET (even)	= +6.749	+0.09142	−0.12600	+0.1416	+0.1688	+0.1459	−0.7502	−0.5194	−0.1732	−0.0598	+6.582	−51.08	* −0.2381	* +0.377	------	0.2245
		s.d.	= (2.290)	(0.01465)	(0.02617)	(0.0495)	(0.0507)	(0.0414)	(0.1782)	(0.1543)	(0.0821)	(0.0590)	(3.241)	(15.90)	(0.5052)	(0.832)	------	------

Note 1, 181 cements, Avg. = 2.551, S.D. = 0.3775
Note 2, 91 cements
Note 3, 90 cements
*Coef./s.d. ratio less than 1.0

TABLE 12–11. *Coefficients for equations for NAE cements relating the percentage gain in weight when moist stored for 28 days following 56 days drying in laboratory air of concretes of a nominal 5 ½ bags cement per cubic yard and a water-cement ratio of 0.635 to various independent variables (OWET)*

Eq. No.	Note		Const.	Air content	C_3S	C_4AF	Al_2O_3	Fe_2O_3	Na_2O	K_2O	SO_3	Loss	Cu	Rb	Zr	Ba	ODRY	S.D.
1	1	OWET	= +0.167														+0.8918	0.1128
		s.d.	= (0.059)														(0.0221)	
2	1	OWET	= +2.742	* +0.0333	−0.01500	+0.04795												0.3287
		s.d.	= (0.267)	(0.0345)	(0.00390)	(0.01177)												
3	1	OWET	= +3.826	+0.1301	−0.01958	+0.03649			−0.7359	−0.7404	−0.1772	−0.0726						0.2494
		s.d.	= (0.231)	(0.0280)	(0.00313)	(0.00900)			(0.1196)	(0.0952)	(0.0617)	(0.0385)						
4	1	OWET	= +3.813	+0.1128	−0.01931	+0.03057			−0.6766	−0.6138	−0.1836	−0.0682	+4.606	−19.28	−0.8397	+0.8131		0.2421
		s.d.	= (0.226)	(0.0285)	(0.00305)	(0.00921)			(0.1191)	(0.1067)	(0.0606)	(0.0382)	(2.354)	(11.01)	(0.4747)	(0.5611)		
4A	2	OWET (odd)	= +3.478	+0.1034	−0.01819	+0.03754			−0.5104	−0.9451	* −0.0252	* −0.0520	+6.409	* −7.38	* −1.9810	+2.4526		0.2258
		s.d.	= (0.285)	(0.0435)	(0.00365)	(0.01297)			(0.1487)	(0.1503)	(0.0903)	(0.0555)	(3.356)	(14.51)	(2.0753)	(0.7364)		
4B	3	OWET (even)	= +3.987	+0.1211	−0.02031	+0.03116			−0.9581	−0.3723	−0.2720	−0.1008	+4.961	−20.25	* −0.3660	* −0.5402		0.2330
		s.d.	= (0.341)	(0.0357)	(0.00483)	(0.01320)			(0.1853)	(0.1509)	(0.0767)	(0.0527)	(3.135)	(16.14)	(0.5087)	(0.8275)		
					CaO	SiO_2												
5	1	OWET	= −2.133	+0.0583	* −0.01062	+0.1882	+0.1026	+0.1896										0.3027
		s.d.	= (1.651)	(0.0321)	(0.02174)	(0.0324)	(0.0419)	(0.0350)										
6	1	OWET	= +5.883	+0.1306	−0.09868	+0.1228	+0.1093	+0.1210	−0.7550	−0.7971	−0.1497	−0.0921						0.2500
		s.d.	= (1.846)	(0.0280)	(0.02091)	(0.0336)	(0.0386)	(0.0312)	(0.1220)	(0.1122)	(0.0694)	(0.0424)						
7	1	OWET	= +6.423	+0.1111	−0.10327	+0.1129	+0.1158	+0.0972	−0.7107	−0.6967	−0.1733	−0.0939	+5.128	−19.63	−0.7477	+1.062		0.2416
		s.d.	= (1.832)	(0.0284)	(0.02051)	(0.0334)	(0.0377)	(0.0324)	(0.1207)	(0.1178)	(0.0679)	(0.0421)	(2.370)	(11.06)	(0.4774)	(0.584)		
7A	2	OWET (odd)	= +7.232	+0.1111	−0.10921	+0.0933	+0.0725	+0.1022	−0.5440	−1.0430	* −0.0243	−0.0797	+6.793	* −5.93	* −1.6909	+2.539		0.2251
		s.d.	= (2.423)	(0.0438)	(0.02734)	(0.0400)	(0.0499)	(0.0457)	(0.1532)	(0.1680)	(0.1010)	(0.0581)	(3.374)	(14.90)	(2.0928)	(0.742)		
7B	3	OWET (even)	= +4.305	+0.1179	−0.08643	+0.1482	+0.1581	+0.1248	−0.9658	−0.4074	−0.2368	−0.1025	+5.113	−20.38	* −0.3430	* −0.228		0.2348
		s.d.	= (2.745)	(0.0369)	(0.03003)	(0.0553)	(0.0559)	(0.0464)	(0.1878)	(0.1617)	(0.0889)	(0.0621)	(3.219)	(16.31)	(0.5225)	(0.910)		

Note 1, 169 cements, Avg. = 2.523, S.D. = 0.3680
Note 2, 85 cements
Note 3, 84 cements
*Coef./s.d. ratio less than 1.0

5.2. Gain of Weight as a Result of Immersion of Air-Dried Specimens in Water

5.2.1. Weight-Gain of Series O Concretes

The frequency distribution of the cements with respect to the weight gain of Series O concretes, moist cured for 14 days then air dried for 56 days, and then placed in water for 28 days, is presented in table 12–9. There was a broad distribution of values and an overlapping of values obtained with concretes made of the different types of cement.

Equations relating the variables associated with the percentage gain of weight on resoaking for the Series O concretes made of AE + NAE cements are presented in table 12–10. Equation 1 indicates a significant relationship between weight-gain and weight-loss during the period of drying in air. The S.D. value obtained for eq 1 was much smaller than was obtained in other equations where air content and other independent variables were used. As indicated in eq 2, an increase in the air content was associated with an increase in the gain of weight of the concrete when rewetted. The additional use of C_3S and C_4AF in eq 3 caused a significant reduction in the S.D. value, and in eq 4, where the variables Na_2O, K_2O, SO_3, and Loss were included, a further significant reduction was obtained. (See table 12–33.) The trace elements Cu, Rb, Zr, and Ba all had coef./s.d. ratios greater than 1.0 in eq 5 where all cements were included, but the coef./s.d. ratios for Rb, Zr, and Ba were less than 1.0 in eqs 5A or 5B, the "odds" or "evens" in the array of cements.

Equations 6, 7, and 8 were calculated using the major oxides instead of the calculated potential compounds as in eqs 3, 4, and 5. There was a significant reduction in variance in the successive eqs 6, 7, and 8 (See table 12–33.), but the S.D. values were about twice as large as that for eq 1 where the weight loss was used as an independent variable. The coef./s.d. ratio of CaO was less than 1.0 in eq 6 but highly significant in eqs 7 and 8.

Equations calculated to indicate the independent variables associated with the weight-gain of Series O concretes made with NAE cements are presented in table 12–11. The independent variables, their coefficients, and the coef./s.d. ratios were in reasonable agreement with those presented in table 12–10 where the AE cements were included. It may be noted that SO_3 had a coef./s.d. ratio less than one in eqs 4A and 7A calculated for one of the smaller groups of cements.

Using the coefficients of the independent variables of eq 5, table 12–10, and their ranges of values, computations were made of the calculated contributions to the OWET values, as well as the calculated ranges of such contributions. The calcualted values are presented in table 12–12. Increases

TABLE 12–12. *Calculated contributions of independent variables to OWET, the percentage gain of weight with resoaking of air-dried Series O concretes made of AE + NAE cements*

Independent variables	Ranges of variables (percent)	Coefficients from eq 5 table 12–10	Calculated contributions to OWET	Calculated range of contributions to OWET
			Const. = +3.84	
Air-content	0 to 11	+0.09755	0 to +1.07	1.07
C_3S	20 to 65	−0.01967	−0.39 to −1.28	0.89
C_4AF	1 to 16	+0.02997	+0.03 to +0.48	0.45
Na_2O	0 to 0.7	−0.6705	0 to −0.47	0.47
K_2O	0 to 1.1	−0.5972	0 to −0.65	0.65
SO_3	1.2 to 3.0	−0.183	−0.22 to −0.55	0.33
Loss*	0.3 to 3.3	−0.0669	−0.02 to −0.22	0.20
Cu	0 to 0.05	+4.89	0 to +0.24	0.24
Rb*	0 to 0.01	−18.5	0 to −0.18	0.18
Zr*	0 to 0.5	−0.8074	0 to −0.41	0.41
Ba*	0 to 0.2	+0.891	0 to −0.18	0.18

*Coefficient of doubtful significance as coef./s.d. ratio was less tban 2.0.

in the air content of the concretes, C_4AF, and possibly Cu were associated with increases in the values for weight-gain. Increases in C_3S, Na_2O, K_2O, and SO_3 were associated with decreases in the values for weight-gain.

5.2.2. Weight-Gain of Series A Concretes

The frequency distribution of the percentage gain of weight when resoaking air-dried concretes made of AE + NAE cements is presented in table 12–13. There was a broad distribution of values and an overlapping of the values of the different types of cement.

Equations relating the variables associated with the weight-gain of the Series A concretes made with AE + NAE cements are presented in table 12–14. No significant relationship was found in

TABLE 12–13. *Frequency distribution of cements with respect to AWET, the percentage weight gain of Series A concretes when air-dried specimens were placed in water for 28 days*

Type cement	Percentage weight gain: 1.8 to 2.0	2.0 to 2.2	2.2 to 2.4	2.4 to 2.6	2.6 to 2.8	2.8 to 3.0	3.0 to 3.2	3.2 to 3.4	3.4 to 3.6	3.6 to 3.8	3.8 to 4.0	Total
	Number of cements											
I	2	8	16	27	13	6	2	4	1	--------	--------	79
IA	--------	--------	2	4	2	--------	--------	--------	--------	--------	--------	8
II	1	4	16	15	13	7	3	3	3	2	--------	67
IIA	--------	--------	1	--------	1	1	--------	--------	--------	--------	--------	3
III	3	4	4	4	4	1	--------	--------	--------	--------	--------	20
IIIA	1	--------	1	1	--------	--------	--------	--------	--------	--------	--------	3
IV, V	--------	--------	1	--------	5	4	--------	3	1	--------	1	15
Total	7	16	41	51	38	19	5	10	5	2	1	195

TABLE 12–14. *Coefficients for equations for AE + NAE cements relating the percentage gain in weight after 28 days moist storage following 56 days of drying of concretes of a nominal 5 ½ bags cement per cubic yard and a 5 ± 1 inch slump to various independent variables (AWET)*

Eq. No.	Note		Const.	C_3A	C_3S	C_4AF		Na_2O	K_2O	SO_3	Loss	Cu	Mn	Ba	Co	Zr	w/c	S.D.
1	1	AWET	= +1.100	----	----	----	----	----	----	----	----	----	----	----	----	----	+2.293	0.3613
		s.d.	= (0.710)	----	----	----	----	----	----	----	----	----	----	----	----	----	(1.115)	----
2	1	AWET	= +3.043	−0.01097	−0.01353	+0.02905	----	----	----	----	----	----	----	----	----	----	----	0.3386
		s.d.	= (0.300)	(0.00991)	(0.00395)	(0.01401)	----	----	----	----	----	----	----	----	----	----	----	----
3	1	AWET	= +3.690	+0.02902	−0.01946	+0.04135	----	−0.7665	−0.8079	−0.0959	−0.0779	----	----	----	----	----	----	0.2681
		s.d.	= (0.252)	(0.00901)	(0.00330)	(0.01123)	----	(0.1258)	(0.1034)	(0.0686)	(0.0409)	----	----	----	----	----	----	----
4	1	AWET	= +3.594	+0.03149	−0.01846	+0.03174	----	−0.7300	−0.7508	−0.1112	−0.0643	+6.210	+0.2703	+0.8975	+23.40	−0.6765	----	0.2588
		s.d.	= (0.249)	(0.00906)	(0.00325)	(0.01135)	----	(0.1247)	(0.1054)	(0.0671)	(0.0404)	(2.604)	(0.1712)	(0.6117)	(14.87)	(0.5049)	----	----
4A	2	AWET (odd)	= +3.089	+0.03090	−0.00953	+0.03686	----	−0.7448	−0.5714	−0.1567	*−0.0524	+5.712	*+0.0380	+1.3755	*−1.71	−0.6046	----	0.2527
		s.d.	= (0.350)	(0.01372)	(0.00442)	(0.01490)	----	(0.1928)	(0.1509)	(0.1128)	(0.0568)	(3.355)	(0.2633)	(0.8599)	(29.86)	(0.5500)	----	----
4B	3	AWET (even)	= +3.949	+0.03601	−0.02672	+0.03122	----	−0.6031	−0.7735	−0.1597	*−0.0085	+8.951	+0.4539	*+0.8569	+28.89	*+2.0102	----	0.2568
		s.d.	= (0.389)	(0.01252)	(0.00508)	(0.01796)	----	(0.1722)	(0.1575)	(0.0883)	(0.0620)	(4.180)	(0.2265)	(0.9437)	(18.73)	(2.4695)	----	----
5	1	AWET	= +2.555	+0.02662	−0.01910	+0.02925	----	−0.7043	−0.6914	−0.1201	−0.0666	+6.253	+0.2649	+1.0081	+21.79	−0.6762	+1.756	0.2564
		s.d.	= (0.567)	(0.00929)	(0.00323)	(0.01131)	----	(0.1242)	(0.1084)	(0.0666)	(0.0401)	(2.579)	(0.1696)	(0.6083)	(14.75)	(0.5000)	(0.865)	----
				CaO	SiO_2	Al_2O_3	Fe_2O_3											
6	1	AWET	= +6.057	−0.1004	+0.1166	+0.1771	+0.0845	−0.7843	−0.8678	*−0.0703	−0.0998	----	----	----	----	----	----	0.2678
		s.d.	= (1.971)	(0.0219)	(0.0363)	(0.0415)	(0.0325)	(0.1265)	(0.1145)	(0.0747)	(0.0448)	----	----	----	----	----	----	----
7	1	AWET	= +6.858	−0.1075	+0.1035	+0.1784	+0.0473	−0.7803	−0.8591	−0.0937	−0.0898	+6.137	----	+1.0641	+22.99	−0.6137	----	0.2588
		s.d.	= (1.952)	(0.0215)	(0.0360)	(0.0405)	(0.0334)	(0.1249)	(0.1124)	(0.0730)	(0.0445)	(2.595)	----	(0.621)	(14.88)	(0.5080)	----	----
7A	2	AWET (odd)	= +3.471	−0.0425	+0.0681	+0.1430	+0.0706	−0.7506	−0.5821	−0.1374	*−0.0546	+5.669	----	+1.4088	*−1.32	−0.6047	----	0.2529
		s.d.	= (2.930)	(0.0307)	(0.0534)	(0.0568)	(0.0464)	(0.1923)	(0.1605)	(0.1274)	(0.0627)	(3.339)	----	(0.9129)	(29.85)	(0.5556)	----	----
7B	3	AWET (even)	= +9.991	−0.1694	+0.1357	+0.2148	+0.0316	−0.7126	−1.0169	−0.1087	*−0.0511	+8.749	----	*+0.9336	+25.07	*+2.3195	----	0.2553
		s.d.	= (2.672)	(0.0307)	(0.0526)	(0.0582)	(0.0506)	(0.1715)	(0.1688)	(0.0923)	(0.0649)	(4.132)	----	(0.9397)	(18.67)	(2.4695)	----	----
8	1	AWET	= +6.034	−0.1128	+0.1044	+0.1650	+0.0461	−0.7544	−0.8010	−0.1054	−0.0954	+6.255	----	+1.2012	+21.13	−0.6025	+1.903	0.2558
		s.d.	= (1.965)	(0.0214)	(0.0356)	(0.0405)	(0.0330)	(0.1240)	(0.1142)	(0.0723)	(0.0440)	(2.566)	----	(0.6170)	(14.73)	(0.5022)	(0.865)	----

Note 1, 175 cements, Avg. = 2.560, S.D. = 0.3647
Note 2, 88 cements
Note 3, 87 cements

*Coef./s.d. ratio less than 1.0

TABLE 12–15. *Coefficients for equations for NAE cements relating the percentage gain in weight after 28 days moist storage following 56 days of drying of concretes of nominal 5 ½ bags cement per cubic yard and a 5 ± 1 inch slump to various independent variables (AWET)*

Eq. No.	Note		Const.	C_3A	C_3S	C_4AF		Na_2O	K_2O	SO_3	Loss	Cu	Mn	Ba	Co	Zr	w/c	S.D.
1	1	AWET	= +0.840														+2.694	0.3670
		s.d.	= (0.972)														(1.516)	
2	1	AWET	= +2.976	−0.01158	−0.01218	+0.03015												0.3443
		s.d.	= (0.316)	(0.01038)	(0.00417)	(0.01462)												
3	1	AWET	= +3.674	+0.02831	−0.01877	+0.04134		−0.7781	−0.8543	−0.0906	−0.0805							0.2702
		s.d.	= (0.265)	(0.00931)	(0.00345)	(0.01160)		(0.1294)	(0.1075)	(0.0708)	(0.0425)							
4	1	AWET	= +3.579	+0.03172	−0.01797	+0.03326		−0.7435	−0.8106	−0.1064	−0.0641	+5.900	+0.1831	+0.8259	+27.61	−0.7568		0.2608
		s.d.	= (0.262)	(0.00942)	(0.00341)	(0.01169)		(0.1288)	(0.1110)	(0.0692)	(0.0420)	(2.648)	(0.1820)	(0.6200)	(15.54)	(0.5124)		
4A	2	AWET (odd)	= +3.187	+0.02440	−0.01449	+0.04201		−0.5370	−0.7969	*−0.0390	*−0.0553	+7.125	*+0.2167	*+0.6678	+42.16	−0.6448		0.2761
		s.d.	= (0.412)	(0.01536)	(0.00501)	(0.01736)		(0.2151)	(0.1878)	(0.1307)	(0.0660)	(4.413)	(0.3058)	(0.9121)	(28.23)	(0.6174)		
4B	3	AWET (even)	= +3.992	+0.03775	−0.02274	*+0.01763		−0.8590	−0.7598	−0.1227	−0.0867	+6.447	*+0.1786	*+0.7026	*+7.80	−1.6910		0.2532
		s.d.	= (0.376)	(0.01307)	(0.00516)	(0.01968)		(0.1737)	(0.1615)	(0.0871)	(0.0631)	(4.137)	(0.2488)	(0.9461)	(20.49)	(1.2639)		
5	1	AWET	= +0.560	+0.01921	−0.01900	+0.03078		−0.7028	−0.6713	−0.1648	−0.0743	+6.973	*+0.1655	+1.287	+19.71	−0.7586	+5.047	0.2484
		s.d.	= (0.786)	(0.00949)	(0.00326)	(0.01115)		(0.1230)	(0.1111)	(0.0675)	(0.0401)	(2.536)	(0.1734)	(0.601)	(14.92)	(0.4880)	(1.245)	
				CaO	SiO_2	Al_2O_3	Fe_2O_3											
6	1	AWET	= +5.700	−0.0946	+0.1162	+0.1752	+0.0867	−0.7939	−0.9048	*−0.0628	−0.0987							0.2704
		s.d.	= (2.051)	(0.0229)	(0.0378)	(0.0435)	(0.0340)	(0.1304)	(0.1189)	(0.0771)	(0.0463)							
7	1	AWET	= +6.421	−0.1010	+0.1040	+0.1785	+0.0510	−0.7857	−0.9036	−0.0869	−0.0864	+5.905		+0.9574	+27.57	−0.7023		0.2602
		s.d.	= (2.022)	(0.0223)	(0.0373)	(0.0423)	(0.0347)	(0.1284)	(0.1163)	(0.0752)	(0.0458)	(2.625)		(0.6287)	(15.50)	(0.5142)		
7A	2	AWET (odd)	= +9.282	−0.1123	*+0.0249	+0.1046	*+0.0444	−0.6569	−0.9446	*−0.0952	−0.1154	+7.474		+1.3804	+51.92	*−0.4491		0.2693
		s.d.	= (2.973)	(0.0323)	(0.0563)	(0.0603)	(0.0520)	(0.2152)	(0.1954)	(0.1352)	(0.0715)	(4.277)		(0.9539)	(27.80)	(0.6109)		
7B	3	AWET (even)	= +2.570	−0.0836	+0.1993	+0.2855	*+0.0457	−0.8818	−0.7762	*−0.0287	−0.0701	+5.471		*+0.6161	*+10.14	−1.8812		0.2539
		s.d.	= (3.123)	(0.0347)	(0.0550)	(0.0650)	(0.0543)	(0.1705)	(0.1626)	(0.0959)	(0.0662)	(4.002)		(0.9480)	(20.76)	(1.2610)		
8	1	AWET	= +3.427	−0.1055	+0.1105	+0.1503	+0.0654	−0.7432	−0.7612	−0.1442	−0.0978	+7.050		+1.4295	+19.48	−0.6987	+5.107	0.2474
		s.d.	= (2.055)	(0.0213)	(0.0355)	(0.0408)	(0.0332)	(0.1225)	(0.1158)	(0.0728)	(0.0437)	(2.511)		(0.6085)	(14.87)	(0.4888)	(1.239)	

Note 1, 163 cements, Avg. = 2.568, S.D. = 0.3694
Note 2, 82 cements
Note 3, 81 cements
*Coef./s.d. ratio less than 1.0

eq 1 where the water/cement ratio was used as an independent variable. (See table 12–33.) The use of the potential compounds C_3A, C_3S, and C_4AF in eq 2 resulted in a significant lowering of the S.D. value. The sign of the coefficient for C_3A was negative and not highly significant in eq 2, but in eq 3 where Na_2O, K_2O, SO_3, and Loss were included as variables, the sign was positive, and the coefficient was highly significant. Including the trace elements Cu, Mn, Ba, Co, and Zr with the other independent variables in eq 4 resulted in a significant reduction in variance. (See table 12–33.) With the use of water/cement ratio in addition to all of these independent variables as in eq 5, the reduction in variance due to the one added variable was significant at the $\alpha = 0.05$ level.

A corresponding series of equations, (eqs 6, 7, and 8) calculated with the major oxides, resulted in S.D. values and "F" ratios comparable to those obtained in eqs 3, 4, and 5 where the potential compounds were used. The coef./s.d. ratio for Mn was less than 1.0 when used with these variables, and therefore was not included in eqs 6, 7, and 8.

In equations 4A, 4B, 7A, and 7B calculated for the "odds" and "evens" in the array of cements, Loss, Fe_2O_3, Mn, Ba, Co, and Zr had coef./s.d. ratios less than 1.0 in one or both of the pairs of equations calculated for the smaller groups of cements.

A similar series of equations indicating the independent variables associated with the absorption of Series A concretes made of NAE cements is presented in table 12–15. The coefficients, the coef./s.d. values and the S.D. values of the equations are in reasonable agreement with those presented in the previous table where the AE cements were included. The coefficients for water/cement ratio were somewhat greater in table 12–15, eqs 5 and 8, than they were in corresponding equations in table 12–14.

Using the coefficients of the independent variables of eq 4, table 12–14, and their ranges of values, computations were made of the calculated contributions to the AWET values, as well as the calculated ranges of such contributions. The calculated values are presented in table 12–16. Increases

TABLE 12–16. *Calculated contributions of independent variables to AWET, the percentage gain of weight with resoaking of air-dried Series A concretes made of AE + NAE cement*

Independent variables	Range of variables (percent)	Coefficients from eq 4 table 12–14	Calculated contributions to AWET	Calculated range of contributions to AWET
			Const. = +3.59	
C_3A	1 to 15	+0.03149	+0.03 to +0.47	0.44
C_3S	20 to 65	−0.01846	−0.37 to −1.20	0.83
C_4AF	1 to 16	+0.03174	+0.03 to +0.51	0.48
Na_2O	0 to 0.7	−0.73	0 to −0.51	0.51
K_2O	0 to 1.1	−0.7508	0 to −0.83	0.83
SO_3*	1.2 to 3.0	−0.1112	−0.13 to −0.33	0.20
Loss*	0.3 to 3.3	−0.0643	−0.02 to −0.21	0.19
Cu	0 to 0.05	+6.21	0 to +0.31	0.31
Mn*	0 to 1.0	+0.2703	0 to +0.27	0.27
Ba*	0 to 0.2	+0.8975	0 to +0.18	0.18
Co*	0 to 0.01	+23.4	0 to +0.23	0.23
Zr*	0 to 0.5	−0.6765	0 to −0.34	0.34

*Coefficient of doubtful significance as coef./s.d. ratio was less than 2.0.

in C_3A, C_4AF, and possibly Cu were associated with increases in absorption. Increases in C_3S, Na_2O, and K_2O were associated with decreases in absorption. Indications of the effects of SO_3, Loss, Mn, Ba, Co, and Zr were of doubtful significance. Variations in C_3S and K_2O had the highest values for the calculated range of contribution to gain of weight when the air-dried concrete specimens were placed in water.

5.3. Ratio of Weight-Gain to Weight-Loss

5.3.1. Weight-Gain/Weight-Loss Ratio of Series O Concretes

The frequency distribution of the weight-gain/weight-loss ratio of the Series O concretes is presented in table 12–17. There was a broad distribution of values and an overlapping of the values obtained for the different types of cement. About 70 percent of the concrete specimens absorbed less water in 28 days of soaking than they had lost in 56 days of drying. The other specimens including most of those made of the air-entraining cements had a gain/loss ratio greater than one.

Equations relating the variables associated with the gain/loss ratio for the Series O concretes made of AE + NAE cements are presented in table 12–18. Equation 1 indicates that the gain/loss ratios are significantly related to the air contents of the concretes. With the additional use of com-

TABLE 12–17. *Frequency distribution of cements with respect to ORWT, the ratio of percentage weight gain divided by the percentage weight loss of Series O concretes. ORWT = OWET/ODRY*

Type cement	Absorption ratio													
	0.82 to 0.85	0.85 to 0.88	0.88 to 0.91	0.91 to 0.94	0.94 to 0.97	0.97 to 1.00	1.00 to 1.03	1.03 to 1.06	1.06 to 1.09	1.09 to 1.12	1.12 to 1.15	1.15 to 1.18	1.18 to 1.21	Total
	Number of cements													
I	------	2	10	28	21	6	12	------	2	------	1	------	------	82
IA	------	------	------	------	------	1	3	2	2	------	------	------	------	8
II	------	3	2	18	24	7	9	4	1	------	------	------	------	68
IIA	------	------	------	------	------	------	1	------	2	------	------	------	------	3
III	1	------	------	1	4	3	4	2	1	3	1	------	------	20
IIIA	------	------	------	------	------	------	------	1	------	------	1	------	1	3
IV, V	------	------	------	3	8	1	3	------	------	------	------	------	------	15
Total	1	5	12	50	57	18	32	9	8	3	3	0	1	199

TABLE 12–18. *Coefficients for equations for AE + NAE cements relating ORWT, the ratio of the percentage weight-gain with 28 day water storage divided by the percentage weight loss with 56 days air storage of Series O concretes to various independent variables (ORWT = OWET/ODRY)*

Eq. No.	Note		Const.	Air content	C_3A	C_4AF	Al_2O_3	Fe_2O_3	Na_2O	MgO	APF	Loss	Cu	Mn	S.D.
1	1	ORWT	= +0.936	+0.0122											0.04457
		s.d.	= (0.005)	(0.0018)											
2	1	ORWT	= +0.847	+0.0121	−0.00210	−0.00288			−0.0563	+0.00464	+0.0000431	−0.0111			0.03752
		s.d.	= (0.031)	(0.0016)	(0.00111)	(0.00152)			(0.0174)	(0.00247)	(0.0000062)	(0.0059)			
3	1	ORWT	= +0.839	+0.0120	−0.00160	−0.00301			−0.0632	+0.00655	+0.0000431	−0.0094	+0.697	−0.0450	0.03685
		s.d.	= (0.031)	(0.0016)	(0.00110)	(0.00154)			(0.0172)	(0.00252)	(0.0000061)	(0.0059)	(0.347)	(0.0242)	
3A	2	ORWT (odd)	= +0.879	+0.0124	−0.00278	−0.00318			−0.0522	+0.00555	+0.0000325	* +0.0011	* −0.010	−0.0800	0.03454
		s.d.	= (0.042)	(0.0022)	(0.00141)	(0.00201)			(0.0203)	(0.00313)	(0.0000082)	(0.0082)	(0.485)	(0.0376)	
3B	3	ORWT (even)	= +0.823	+0.0122	* −0.00092	−0.00390			−0.1015	+0.00708	+0.0000519	−0.0184	+1.557	* −0.0313	0.03878
		s.d.	= (0.047)	(0.0024)	(0.00179)	(0.00242)			(0.0324)	(0.00418)	(0.0000091)	(0.0086)	(0.538)	(0.0333)	
4	1	ORWT	= +0.847	+0.0121			−0.00554	−0.00526	−0.0564	+0.00463	+0.0000431	−0.0111			0.03753
		s.d.	= (0.031)	(0.0016)			(0.00294)	(0.00394)	(0.0174)	(0.00247)	(0.0000062)	(0.0059)			
5	1	ORWT	= +0.839	+0.0120			−0.00422	−0.00650	−0.0632	+0.00653	+0.0000431	−0.0094	+0.699	−0.0451	0.03685
		s.d.	= (0.031)	(0.0016)			(0.00292)	(0.00410)	(0.0172)	(0.00252)	(0.0000061)	(0.0059)	(0.347)	(0.0242)	
5A	2	ORWT (odd)	= +0.879	+0.0124			−0.00737	* −0.00507	−0.0522	+0.00553	+0.0000324	* +0.0011	* −0.008	−0.0800	0.03454
		s.d.	= (0.042)	(0.0022)			(0.00374)	(0.00543)	(0.0203)	(0.00313)	(0.0000082)	(0.0082)	(0.485)	(0.0376)	
5B	3	ORWT (even)	= +0.823	+0.0123			* −0.00242	−0.01036	−0.1016	+0.00707	+0.0000519	−0.0184	+1.560	* −0.0313	0.03878
		s.d.	= (0.047)	(0.0024)			(0.00475)	(0.00624)	(0.0324)	(0.00418)	(0.0000091)	(0.0086)	(0.538)	(0.0333)	

*Coef./s.d. ratio less than 1.0. Note 1, 177 cements, Avg. = 0.9621, S.D. = 0.04971 Note 2, 89 cements Note 3, 88 cements

TABLE 12–19. *Coefficients for equations for NAE cements relating the ratio of the percentage weight-gain with 28 days water storage divided by the percentage weight loss with 56 days of air storage of Series O concretes to various independent variables (ORWT = OWET/ODRY)*

Eq. No.	Note		Const.	Air content	C_3A	C_4AF	Al_2O_3	Fe_2O_3	Na_2O	MgO	APF	Loss	Cu	Mn	S.D.
1	1	ORWT	= +0.936	+0.0124											0.04458
		s.d.	= (0.008)	(0.0046)											
2	1	ORWT	= +0.854	+0.0145	−0.00255	−0.00299			−0.0596	+0.00436	+0.0000428	−0.0139			0.03748
		s.d.	= (0.033)	(0.0041)	(0.00113)	(0.00155)			(0.0177)	(0.00251)	(0.0000064)	(0.0061)			
3	1	ORWT	= +0.849	+0.0124	−0.00200	−0.00319			−0.0653	+0.00611	+0.0000429	−0.0125	+0.665	−0.0441	0.03689
		s.d.	= (0.032)	(0.0041)	(0.00114)	(0.00158)			(0.0176)	(0.00255)	(0.0000063)	(0.0060)	(0.355)	(0.0251)	
3A	2	ORWT (odd)	= +0.857	+0.0150	−0.00310	−0.00235			−0.0558	+0.00607	+0.0000370	* −0.0055	+0.681	−0.0665	0.03762
		s.d.	= (0.045)	(0.0068)	(0.00156)	(0.00224)			(0.0226)	(0.00379)	(0.0000096)	(0.0091)	(0.517)	(0.0473)	
3B	3	ORWT (even)	= +0.848	+0.0114	* −0.00068	−0.00381			−0.0892	+0.00587	+0.0000467	−0.0188	* +0.329	−0.0430	0.03736
		s.d.	= (0.051)	(0.0059)	(0.00175)	(0.00246)			(0.0324)	(0.00400)	(0.0000093)	(0.0090)	(0.559)	(0.0317)	
4	1	ORWT	= +0.854	+0.0145			−0.00672	−0.00482	−0.0596	+0.00434	+0.0000428	−0.0139			0.03749
		s.d.	= (0.033)	(0.0041)			(0.00301)	(0.00402)	(0.0177)	(0.00251)	(0.0000064)	(0.0061)			
5	1	ORWT	= +0.849	+0.0124			−0.00526	−0.00636	−0.0653	+0.00610	+0.0000429	−0.0125	+0.667	−0.0441	0.03689
		s.d.	= (0.032)	(0.0041)			(0.00301)	(0.00422)	(0.0176)	(0.00255)	(0.0000063)	(0.0060)	(0.355)	(0.0251)	
5A	2	ORWT (odd)	= +0.858	+0.0149			−0.00820	* −0.00200	−0.0558	+0.00607	+0.0000370	* −0.0056	+0.686	−0.0663	0.03762
		s.d.	= (0.045)	(0.0067)			(0.00413)	(0.00618)	(0.0226)	(0.00379)	(0.0000096)	(0.0091)	(0.517)	(0.0473)	
5B	3	ORWT (even)	= +0.847	+0.0114			* −0.00171	−0.01043	−0.0893	+0.00586	+0.0000468	−0.0188	* +0.329	−0.0431	0.03736
		s.d.	= (0.051)	(0.0059)			(0.00463)	(0.00633)	(0.0324)	(0.00400)	(0.0000093)	(0.0090)	(0.559)	(0.0317)	

*Coef./s.d. ratio less than 1.0. Note 1, 165 cements, Avg. = 0.9564, S.D. = 0.04543 Note 2, 83 cements Note 3, 82 cements

monly determined variables in eq 2 a further highly significant reduction of variance was achieved. (See also table 12–33.) The use of Cu and Mn as independent variables together with the other independent variables in eq 3 resulted in a slightly lower S.D. value, but, as indicated in table 12–33 this was significant at the $\alpha = 0.05$ level.

Equations 3A and 3B, calculated for the "odds" and "evens" in the array of cements, indicated that C_3A, Loss, Cu, and Mn had coef./s.d. ratios less than 1.0 in one or the other of the equations for the smaller groups of cements.

In eqs 4 and 5, the oxides were used as independent variables instead of the potential compounds. A highly significant reduction of variance resulted from use of the commonly determined variables in eq 4, but with the additional use of the trace elements in eq 5 the reduction of variance was significant at the $\alpha = 0.05$ probability level.

A corresponding series of equations for the gain/loss ratio of Series O concretes is presented in table 12–19. The coef./s.d. ratio for the air content in eq 1, table 12–19, was smaller than the corresponding one in table 12–18 where the AE cements were included. The use of commonly determined variables C_3A, C_4AF, Na_2O, MgO, APF, and Loss in eq 2 resulted in a highly significant reduction in variance. The additional use of Cu and Mn in eq 3 resulted in a reduction of variance significant at the $\alpha = 0.05$ level. (See table 12–33.)

The use in eqs 4 and 5 of the oxides Al_2O_3 and Fe_2O_3 instead of the calculated potential compounds resulted in an equivalent reduction of the S.D. values.

Equations calculated for the "odds" and "evens" in the array of cements (eqs 3A, 3B, 5A, and 5B) had instances where the coef./s.d. ratio was less than 1.0 for C_3A, Al_2O_3, Fe_2O_3, Loss, and Cu.

Using the coefficients of the independent variables of eq 3 of table 12–18 and their ranges, computations were made of the calculated contributions to the OWTR ratio, as well as the calculated ranges of such contributions. The calculated values are presented in table 12–20. Increases of the air content, fineness, and possibly MgO and Cu were associated with an increase of the ORWT ratio. Increase in Na_2O was associated with a decrease of the ORWT ratio.

TABLE 12–20. *Calculated contributions of independent variables to ORWT, the ratio of percentage absorption to percentage weight loss on drying of Series O concretes made of AE + NAE cements*

Independent variables	Range of variables (percent)	Coefficients from eq 3 table 12–18	Calculated contributions to ORWT	Calculated range of contributions to ORWT
			Const. = +0.839	
Air-content	0 to 11	+0.012	0 to +0.132	0.132
C_3A**	1 to 15	−0.0016	−0.002 to −0.024	0.022
C_4AF**	1 to 16	−0.00301	−0.003 to −0.048	0.045
Na_2O	0 to 0.7	−0.0632	0 to −0.044	0.044
MgO	0 to 5.0	+0.00655	0 to +0.033	0.033
APF	*2500 to 5500	+0.0000431	+0.107 to +0.237	0.130
Loss**	0.3 to 3.3	−0.0094	−0.003 to −0.031	0.028
Cu	0 to 0.05	+0.697	0 to +0.034	0.034
Mn**	0 to 1.0	−0.0450	0 to −0.045	0.045

*cm^2/g.
**Coefficient of doubtful significance as coef./s.d. ratio was less than 2.0.

5.3.2. Weight-Gain/Weight-Loss Ratio for Series A Concretes

The frequency distribution of the ratio of percentage absorption to the percentage weight loss of Series A concretes is presented in table 12–21. There was a broad distribution of values and an overlapping of the values for the different types of cement. About one-fourth of the specimens had a slightly greater absorption than loss on drying, and these included concretes made with 11 of the 14 air-entraining cements.

Equations indicating the variables associated with ARWT are presented in table 12–22. The use of the commonly determined variables, air content, Na_2O, MgO, and APF in eq 1 resulted in a significant reduction in variance. The additional use in eq 2 of C_4AF, Ba, Cu, SrO, and V resulted in a reduction of variance significant at the 5.0-percent level. (See table 12–33.)

In equations 2A and 2B calculated for the "odds" and "evens" in the array of cements, the coef./s.d. ratios for C_4AF, MgO, Ba, SrO, and V

TABLE 12–21. *Frequency distribution of cements with respect to ARWT, the ratio of percentage weight gain divided by the percentage weight loss of Series A concretes. ARWT = AWET/ADRY*

Type cement	Absorption ratio											
	0.82 to 0.85	0.85 to 0.88	0.88 to 0.91	0.91 to 0.94	0.94 to 0.97	0.97 to 1.00	1.00 to 1.03	1.03 to 1.06	1.06 to 1.09	1.09 to 1.12	1.12 to 1.15	Total
	Number of cements											
I		3	12	20	23	8	7	2	3	1		79
IA					3		2	2	1			8
II	1	2	3	22	17	7	10	3	2			67
IIA							1	1	1			3
III			1	2	6	2	3	2	4			20
IIIA							1				2	3
IV, V			1	2	6	4		2				15
Total	1	5	17	46	55	21	24	12	11	1	2	195

TABLE 12–22. *Coefficients for equations for AE + NAE cements relating ARWT, the ratio of the percentage weight-gain with 28 days water-storage divided by the percentage weight loss with 56 days of air storage of Series A concretes to various independent variables (ARWT = AWET/ADRY)*

Eq. No.	Note		Const.	ADRY	Air content	C_4AF	Fe_2O_3	Na_2O	MgO	APF	Ba	Cu	SrO	V	S.D.
1	1	ARWT s.d.	= +0.877 = (0.025)		+0.00731 (0.00167)			−0.0706 (0.0205)	+0.00414 (0.00294)	+0.0000213 (0.0000066)					0.04436
2	1	ARWT s.d.	= +0.904 = (0.032)		+0.00730 (0.00166)	−0.00276 (0.00157)		−0.0634 (0.0213)	+0.00559 (0.00303)	+0.0000195 (0.0000066)	+0.195 (0.110)	+0.985 (0.407)	−0.0596 (0.0380)	−0.315 (0.204)	0.04321
2A	2	ARWT (odd) s.d.	= +0.909 = (0.047)		+0.00556 (0.00203)	−0.00382 (0.00243)		−0.0643 (0.0334)	+0.00837 (0.00436)	+0.0000181 (0.0000095)	* +0.212 (0.318)	+0.996 (0.615)	* −0.0428 (0.0544)	* −0.232 (0.325)	0.04353
2B	3	ARWT (even) s.d.	= +0.896 = (0.046)		+0.01196 (0.00310)	* −0.00138 (0.00223)		−0.0665 (0.0301)	* +0.00198 (0.00452)	+0.0000220 (0.0000097)	+0.171 (0.133)	+0.786 (0.594)	−0.0999 (0.0567)	−0.443 (0.276)	0.04387
3	1	ARWT s.d.	= +0.977 = (0.041)	−0.0257 (0.0093)	+0.00663 (0.00164)	** −0.00180 (0.00158)		−0.0761 (0.0213)	** +0.00553 (0.00297)	+0.0000161 (0.0000066)	** +0.191 (0.108)	+1.222 (0.408)	** −0.0556 (0.0373)	** −0.251 (0.201)	0.04235
4	1	ARWT s.d.	= +0.892 = (0.031)		+0.00708 (0.00465)		* −0.00399 (0.02053)	−0.0713 (0.0205)	+0.00389 (0.00297)	+0.0000209 (0.0000066)					0.04439
5	1	ARWT s.d.	= +0.905 = (0.032)		+0.00730 (0.00166)		−0.00849 (0.00479)	−0.0634 (0.0213)	+0.00558 (0.00303)	+0.0000195 (0.0000066)	+0.195 (0.110)	+0.987 (0.407)	−0.0596 (0.0380)	−0.315 (0.204)	0.04320
5A	2	ARWT (odd) s.d.	= +0.909 = (0.047)		+0.00557 (0.00202)		−0.01173 (0.00741)	−0.0642 (0.0334)	+0.00835 (0.00436)	+0.0000181 (0.0000095)	* +0.211 (0.317)	+0.996 (0.615)	* −0.0428 (0.0544)	* −0.233 (0.325)	0.04353
5B	3	ARWT (even) s.d.	= +0.896 = (0.046)		+0.01196 (0.00310)		* −0.00428 (0.00682)	−0.0664 (0.0301)	* +0.00198 (0.00452)	+0.0000220 (0.0000097)	+0.171 (0.133)	+0.789 (0.594)	−0.0999 (0.0567)	−0.443 (0.276)	0.04386
6	1	ARWT s.d.	= +0.978 = (0.041)	−0.0257 (0.0093)	+0.00663 (0.00164)		** −0.00562 (0.00481)	−0.0761 (0.0213)	** +0.00552 (0.00297)	+0.0000161 (0.0000066)	** +0.192 (0.108)	+1.226 (0.408)	** −0.0556 (0.0373)	** −0.250 (0.201)	0.04234

*Coef./s.d. ratio less than 1.0.
**Coef./s.d. ratio less than 1.0 in "odds" or "evens."

Note 1, 173 cements, Avg. = 0.9605, S.D. = 0.04956
Note 2, 87 cements
Note 3, 86 cements

TABLE 12–23. *Coefficients for equations for NAE cements relating the ratio of the percentage weight-gain with 28 days water-storage divided by the percentage weight loss with 56 days air storage of Series A concretes to various independent variables (ARWT = AWET/ADRY)*

Eq. No.	Note		Const.	ADRY	Air content	C_4AF	Fe_2O_3	Na_2O	MgO	APF	Ba	Cu	SrO	V	S.D.
1	1	ARWT	= +0.887		+0.00900			−0.0763	+0.00324	+0.0000183					0.04383
		s.d.	= (0.026)		(0.00400)			(0.0207)	(0.00296)	(0.0000068)					
2	1	ARWT	= +0.921		+0.00769	−0.00273		−0.0653	+0.00509	+0.0000159	+0.190	+0.958	−0.0865	−0.306	0.04233
		s.d.	= (0.033)		(0.00419)	(0.00158)		(0.0213)	(0.00304)	(0.0000067)	(0.109)	(0.406)	(0.0393)	(0.205)	
2A	2	ARWT (odd)	= +0.913		+0.00957	* −0.00023		−0.0653	+0.00721	+0.0000106	* +0.193	* +0.538	−0.0778	−0.672	0.04413
		s.d.	= (0.049)		(0.00597)	(0.00028)		(0.0363)	(0.00481)	(0.0000100)	(0.334)	(0.686)	(0.0630)	(0.334)	
2B	3	ARWT (even)	= +0.924		* +0.00548	−0.00407		−0.0693	* +0.00380	+0.0000198	+0.133	+1.111	−0.0852	* −0.080	0.04222
		s.d.	= (0.047)		(0.00628)	(0.00217)		(0.0289)	(0.00410)	(0.0000098)	(0.133)	(0.578)	(0.0531)	(0.276)	
3	1	ARWT	= +0.990	−0.0247	** +0.00513	** −0.00188		−0.0755	+0.00511	** +0.0000135	** +0.192	+1.215	−0.0806	** −0.224	0.04153
		s.d.	= (0.042)	(0.0095)	(0.00415)	(0.00158)		(0.0213)	(0.00298)	(0.0000067)	(0.107)	(0.410)	(0.0386)	(0.203)	
4	1	ARWT	= +0.902		+0.00357		* −0.00352	−0.0769	+0.00304	+0.0000178					0.04389
		s.d.	= (0.032)		(0.00405)		(0.00467)	(0.0208)	(0.00298)	(0.0000068)					
5	1	ARWT	= +0.921		+0.00770		−0.00839	−0.0653	+0.00508	+0.0000159	+0.190	+0.960	−0.0865	−0.306	0.04232
		s.d.	= (0.033)		(0.00411)		(0.00481)	(0.0213)	(0.00304)	(0.0000067)	(0.109)	(0.406)	(0.0393)	(0.205)	
5A	2	ARWT (odd)	= +0.914		+0.00955		* −0.00087	−0.0653	+0.00721	+0.0000106	* +0.196	* +0.546	−0.0779	−0.670	0.04413
		s.d.	= (0.049)		(0.00596)		(0.00839)	(0.0363)	(0.00481)	(0.0000100)	(0.334)	(0.686)	(0.0630)	(0.334)	
5B	3	ARWT (even)	= +0.924		* +0.00549		−0.01244	−0.0693	* +0.00377	+0.0000198	+0.134	+1.109	−0.0851	* −0.080	0.04221
		s.d.	= (0.047)		(0.00628)		(0.00662)	(0.0288)	(0.00409)	(0.0000098)	(0.132)	(0.577)	(0.0531)	(0.276)	
6	1	ARWT	= +0.990	−0.0247	** +0.00513		** −0.00584	−0.0755	+0.00510	** +0.0000135	** +0.192	+1.218	−0.0807	** −0.223	0.04153
		s.d.	= (0.041)	(0.0094)	(0.00415)		(0.00482)	(0.0213)	(0.00298)	(0.0000067)	(0.107)	(0.410)	(0.0386)	(0.203)	

*Coef./s.d. ratio less than 1.0.
**Coef./s.d. ratio less than 1.0 in "odds" or "evens."

Note 1, 161 cements, Avg. = 0.9563, S.D. = 0.04696
Note 2, 81 cements
Note 3, 80 cements

were less than 1.0 in one or the other of the smaller groups.

The use in eq 3 of ADRY, the percentage loss on drying as an independent variable, together with those previously mentioned, resulted in a further significant reduction of variance. In eqs 3A and 3B, calculated for the "odds" and "evens" (not presented in the table), there were instances where the same independent variables had coef./s.d. ratios less than 1.0 as was indicated in eqs 2A and 2B. Equations 4, 5, and 6 were calculated using Fe_2O_3 instead of C_4AF as an independent variable. The coef./s.d. ratio for Fe_2O_3 was less than 1.0 in eq 4 and of doubtful significance in eqs 5 and 6. The use of the trace elements in eq 5 resulted in a reduction of variance significant at the 5.0-percent level. (See table 12–33.)

A corresponding series of equations for the NAE cements is presented in table 12–23. The coefficients, the s.d. values for the coefficients, and the S.D. values are in reasonable agreement with those of the previous table where the AE cements were included.

Using the coefficients of the independent variables of eq 2 table 12–22 and the ranges of these variables, calculations were made of the estimated contributions to ARWT. The results of these calculations are presented in table 12–24 together with the calculated range of these contributions.

TABLE 12–24. *Calculated contributions of independent variables to ARWT, the ratio of absorption to weight loss on drying of Series A concretes made of AE + NAE cements*

Independent variables	Range of variables (percent)	Coefficients from eq 2 table 12–22	Calculated contributions to ARWT	Calculated range of contributions to ARWT
			Const. = +0.904	
Air-content	0 to 13	+0.0073	0 to +0.095	0.095
C_4AF**	1 to 16	−0.00276	−0.003 to −0.044	0.041
Na_2O	0 to 0.7	−0.0634	0 to −0.044	0.044
MgO**	0 to 5	+0.00559	0 to +0.028	0.028
APF	*2500 to 5500	+0.0000195	+0.049 to +0.107	0.058
Ba**	0 to 0.2	+0.195	0 to +0.039	0.039
Cu	0 to 0.05	+0.985	0 to +0.049	0.049
SrO**	0 to 0.4	−0.0596	0 to −0.024	0.024
V**	0 to 0.1	−0.315	0 to −0.032	0.032

*cm^2/g.
**Coefficient of doubtful significance as coef./s.d. ratio was less than 2.0.

Increases of the air-content, fineness, and possibly Cu were associated with an increase of the ARWT ratio. Increase of Na_2O was associated with decrease of the ARWT ratio.

5.4. Ratio of Weight-Gain Minus Weight-Loss to Weight-Loss

5.4.1. Absorption Ratio for Series O Concretes

The frequency distribution of the cements with respect to OWTR, the ratio (ODRY-OWET)/ODRY, is presented in table 12–25. There was a fairly broad distribution of values and an overlapping of the values obtained with the different types of cement.

Equations are presented in table 12–26 indicating the independent variables associated with OWTR. The use of the commonly determined independent variables C_3A, C_3S, C_4AF, Na_2O, SO_3, APF, Loss, MgO, and air content in eq 1 resulted in a significant reduction of variance. The additional use of Cu and SrO in eq 2 resulted in a further reduction of variance significant at the 5.0-percent level.

In eq 2B the coef./s.d. ratios of C_4AF, Na_2O, and Cu were less than 1.0 for this group of results.

Equations 3 and 4 were calculated using the major oxides instead of the calculated potential compounds. The coef./s.d. ratios for SO_3, Loss, and MgO were less than 1.0 when included with these variables and were not retained in these equations.

The corresponding series of equations for the NAE cements is presented in table 12–27. The coefficients, their s.d. values, and the S.D. values of the equations are in reasonable agreement with those of the previous table where the AE cements were included.

Using the coefficients of the independent variables of eq 2, table 12–26, together with the ranges of these variables, calculations were made of the estimated contributions to OWTR and the ranges of such contributions. These calculated values are presented in table 12–28. Increases of air content, fineness, and possibly C_3S, Cu, and MgO were

TABLE 12–25. *Frequency distribution of cements with respect to OWTR, the ratio of the difference between weight loss and weight-gain to the weight loss of Series O concretes. OWTR = (ODRY − OWET)/ODRY*

Type cement	Absorption ratio													
	−0.21 to −0.18	−0.18 to −0.15	−0.15 to −0.12	−0.12 to −0.09	−0.09 to −0.06	−0.06 to −0.03	−0.03 to 0	0 to +0.03	+0.03 to 0.06	0.06 to 0.09	0.09 to 0.12	0.12 to 0.15	0.15 to 0.18	Total
	Number of cements													
I					2	1	2	14	21	29	10	3		82
IA					1	3	2	1	1					8
II					1	4	0	15	25	18	2	3		68
IIA					2		1							3
III				4	1	2	1	5	5	1			1	20
IIIA	1		1			1								3
IV, V							1	3	7	4				15
Total	1	0	1	4	7	11	7	38	59	52	12	6	1	199

Table 12–26. *Coefficients for equations for AE + NAE cements relating the ratio of gain with water storage divided by the percentage weight-loss of Series O con*

Eq. No.	Note		Const.	C_3A	C_3S	C_4AF	SiO_2	Al_2O_3
1	1	OWTR	= +0.181	+0.00299	−0.00087	+0.00220	----	----
		s.d.	= (0.035)	(0.00114)	(0.00046)	(0.00146)	----	----
2	1	OWTR	= +0.193	+0.00199	−0.00094	+0.00257	----	----
		s.d.	= (0.035)	(0.00122)	(0.00045)	(0.00147)	----	----
2A	2	OWTR (odd)	= +0.184	+0.00300	−0.00061	+0.00476	----	----
		s.d.	= (0.049)	(0.00182)	(0.00058)	(0.00215)	----	----
2B	2	OWTR (even)	= +0.221	+0.00183	−0.00164	* +0.00140	----	----
		s.d.	= (0.060)	(0.00172)	(0.00074)	(0.00217)	----	----
3	1	OWTR	= −0.168	----	----	----	+0.0095	+0.0162
		s.d.	= (0.138)	----	----	----	(0.0044)	(0.0056)
4	1	OWTR	= −0.217	----	----	----	+0.0113	+0.0155
		s.d.	= (0.138)	----	----	----	(0.0044)	(0.0057)
4A	2	OWTR (odd)	= −0.234	----	----	----	+0.0115	+0.0168
		s.d.	= (0.189)	----	----	----	(0.0060)	(0.0083)
4B	2	OWTR (even)	= −0.231	----	----	----	+0.0121	+0.0157
		s.d.	= (0.208)	----	----	----	(0.0067)	(0.0082)

Note 1, 176 cements, Avg. = 0.0395, S.D. = 0.04671
Note 2, 88 cements
*Coef./s.d. ratio less than 1.0.

Table 12–27. *Coefficients for equations for NAE cements relating the ratio of differences water storage divided by the percentage weight-loss of Series O concretes*

Eq. No.	Note		Const.	C_3A	C_3S	C_4AF	SiO_2	Al_2O_3
1	1	OWTR	= +0.178	+0.00347	+0.00093	+0.00215	----	----
		s.d.	= (0.037)	(0.00114)	(0.00047)	(0.00147)	----	----
2	1	OWTR	= +0.189	+0.00223	−0.00101	+0.00241	----	----
		s.d.	= (0.036)	(0.00121)	(0.00046)	(0.00148)	----	----
2A	2	OWTR (odd)	= +0.153	+0.00279	−0.00079	+0.00579)	----	----
		s.d.	= (0.048)	(0.00167)	(0.00056)	(0.00203)	----	----
2B	2	OWTR (even)	= +0.226	* +0.00176	−0.00141	* +0.00042	----	----
		s.d.	= (0.058)	(0.00182)	(0.00078)	(0.00227)	----	----
3	1	OWTR	= −0.150	----	----	----	+0.00885	+0.0167
		s.d.	= (0.141)	----	----	----	(0.00451)	(0.0057)
4	1	OWTR	= −0.204	----	----	----	+0.01070	+0.0156
		s.d.	= (0.141)	----	----	----	(0.00452)	(0.0058)
4A	2	OWTR (odd)	= −0.325	----	----	----	+0.01329	+0.0189
		s.d.	= (0.176)	----	----	----	(0.00546)	(0.0075)
4B	2	OWTR (even)	= −0.141	----	----	----	+0.00974	+0.0135
		s.d.	= (0.231)	----	----	----	(0.00758)	(0.0091)

Note 1, 164 cements, Avg. = 0.0454, S.D. = 0.04165
Note 2, 82 cements
*Coef./s.d. ratio less than 1.0.

Table 12–28. *Calculated contributions of independent variables to OWTR, the ratio (ODRY−OWET)/ODRY for Series O concretes made of AE + NAE cements*

Independent variables	Range of variables (percent)	Coefficients from eq 2 table 12–26	Calculated contributions to OWTR	Calculated range of contributions to OWTR
			Const. = +0.193	
C_3A**	1 to 15	+0.00199	+0.002 to +0.030	0.028
C_3S	20 to 65	−0.00094	−0.018 to −0.061	0.043
C_4AF**	1 to 16	+0.00257	+0.003 to +0.041	0.038
Na_2O	0 to 0.7	+0.0421	0 to +0.029	0.029
SO_3**	1.2 to 3.3	−0.0187	−0.022 to −0.062	0.040
APF	*2500 to 5500	−0.000027	−0.068 to −0.148	0.080
Loss**	0.3 to 3.3	+0.0102	+0.003 to +0.034	0.031
MgO	0 to 5	−0.0070	0 to −0.035	0.035
Air-content	0 to 11	−0.0122	0 to −0.134	0.134
Cu	0 to 0.05	−0.795	0 to −0.040	0.040
SrO**	0 to 0.4	+0.0516	0 to +0.021	0.021

*cm^2/g.
**Coefficient of doubtful significance as coef./s.d. ratio was less than 2.0.

associated with decreases of the OWTR ratio. Increases of Na_2O were possibly associated with increases of the OWTR ratio. The coefficients for C_3A, C_4AF, Loss, and SrO were of doubtful significance.

5.4.2. Absorption Ratio for Series A Concretes

The frequency distribution of AWTR, the ratio of (ADRY-AWET)/AWET, is presented in table 12–29. There was a broad distribution of values and an overlapping of the values obtained with the different types of cement.

Equations are presented in table 12–30 indicating the independent variables associated with AWTR. Equation 1 indicates that an increase of the air content was associated with a decrease of the absorption ratio. (See also table 12–33.) The

differences between the percentage weight-loss on air drying and the percentage weight-cretes to various independent variables OWTR = (ODRY − OWET)/ODRY

Fe_2O_3	Na_2O	SO_3	APF	Loss	MgO	Air content	Cu	SrO	S.D.
	+0.0453 (0.0163)	−0.0148 (0.0097)	−0.000029 (0.000007)	+0.0098 (0.0055)	−0.0060 (0.0023)	−0.0122 (0.0015)			0.03473
	+0.0421 (0.0167)	−0.0187 (0.0097)	−0.000027 (0.000007)	+0.0102 (0.0054)	−0.0070 (0.0023)	−0.0122 (0.0015)	−0.795 (0.322)	+0.0516 (0.0340)	0.03402
	+0.0773 (0.0227)	−0.0313 (0.0156)	−0.000032 (0.000010)	+0.0095 (0.0082)	−0.0089 (0.0036)	−0.0113 (0.0021)	−1.416 (0.476)	+0.0588 (0.0500)	0.03417
	*−0.0099 (0.0270)	−0.0137 (0.0130)	−0.000022 (0.000010)	+0.0109 (0.0076)	−0.0047 (0.0033)	−0.0139 (0.0022)	*−0.477 (0.480)	+0.0527 (0.0476)	0.03338
+0.00607 (0.00382)	+0.0471 (0.0164)		−0.000025 (0.000006)			−0.0127 (0.0015)			0.03529
+0.00928 (0.00399)	+0.0456 (0.0170)		−0.000024 (0.000006)			−0.0128 (0.0015)	−0.740 (0.327)	+0.0386 (0.0343)	0.03480
+0.01415 (0.00579)	+0.0857 (0.0234)		−0.000028 (0.000009)			−0.0126 (0.0022)	−1.284 (0.493)	*+0.0250 (0.0494)	0.03555
+0.00744 (0.00569)	*−0.0042 (0.0265)		−0.000020 (0.000008)			−0.0138 (0.0021)	−0.571 (0.477)	+0.0552 (0.0481)	0.03380

between the percentage weight-loss on air drying and the percentage weight-gain with to various independent variables OWTR = (ODRY − OWET)/ODRY

Fe_2O_3	Na_2O	SO_3	APF	Loss	MgO	Air content	Cu	SrO	S.D.
	+0.0480 (0.0165)	−0.0152 (0.0098)	−0.000028 (0.000007)	+0.0127 (0.0056)	−0.0057 (0.0024)	−0.0150 (0.0038)			0.034
	+0.0408 (0.0168)	−0.0199 (0.0097)	−0.000026 (0.000007)	+0.0141 (0.0055)	−0.0068 (0.0023)	−0.0136 (0.0037)	−0.728 (0.326)	+0.0727 (0.0348)	0.033
	+0.0792 (0.0205)	−0.0240 (0.0144)	−0.000025 (0.000009)	*+0.0061 (0.0086)	−0.0086 (0.0031)	−0.0156 (0.0055)	*−0.403 (0.457)	+0.0590 (0.0524)	0.030
	*+0.0043 (0.0285)	*−0.0134 (0.0141)	−0.000029 (0.000011)	+0.0184 (0.0079)	−0.0058 (0.0037)	−0.0122 (0.0056)	−0.927 (0.477)	+0.0885 (0.0526)	0.035
+0.00489 (0.00389)	+0.0500 (0.0167)		−0.000024 (0.000006)			−0.0162 (0.0038)			0.035
+0.00810 (0.00410)	+0.0452 (0.0173)		−0.000022 (0.000006)			−0.0151 (0.0038)	−0.661 (0.335)	+0.0538 (0.0355)	0.034
+0.01923 (0.00561)	+0.0836 (0.0205)		+0.000021 (0.000008)			−0.0147 (0.0055)	*−0.344 (0.457)	*+0.0328 (0.0483)	0.031
*+0.00079 (0.00592)	*−0.0052 (0.0295)		−0.000023 (0.000009)			−0.0151 (0.0056)	−0.729 (0.488)	+0.0894 (0.0541)	0.036

TABLE 12–29. *Frequency distribution of cements with respect to AWTR, the ratio of the difference between weight-loss and weight-gain divided by the weight-loss. AWTR = (ADRY − AWET)/ADRY*

Type cement	Absorption ratio											
	−0.15 to −0.12	−0.12 to −0.09	−0.09 to −0.06	−0.06 to −0.03	−0.03 to 0	0 to 0.03	+0.03 to 0.06	0.06 to 0.09	0.09 to 0.12	0.12 to 0.15	0.15 to 0.18	Total
	Number of cements											
I		1	3	2	6	7	24	21	11	4		79
IA			1	2	1	1	3					8
II			1	3	3	13	17	24	3	1	1	66
IIA			1	1		1						3
III			4	1	1	3	8	2	1			20
IIIA	2					1						3
IV, V				2		4	5	3	1			15
Total	2	1	10	11	11	30	57	50	16	5	1	194

TABLE 12–30. *Coefficients for equations for AE + NAE cements relating the ratio of the difference between the percentage weight-loss on air drying and the percentage weight-gain with water storage divided by the percentage weight-loss of Series A concretes to various independent variables (AWTR = (ADRY − AWET)/ADRY)*

Eq. No.	Note		Const.	Air content	C_3A	C_4AF	Fe_2O_3	Na_2O	APF	MgO	Cu	SrO	S.D.
1	1	AWTR	= +0.0514	−0.00527									0.04732
		s.d.	= (0.0050)	(0.00172)									
2	1	AWTR	= +0.0627	−0.00531	+0.00184	+0.00258		+0.0716	−0.0000161	−0.00452			0.04455
		s.d.	= (0.0369)	(0.00170)	(0.00131)	(0.00182)		(0.0207)	(0.0000065)	(0.00296)			
3	1	AWTR	= +0.0758	−0.00560		+0.00291		+0.0651	−0.0000160	−0.00597	−1.032	+0.0857	0.04324
		s.d.	= (0.0306)	(0.00164)		(0.00157)		(0.0211)	(0.0000063)	(0.00290)	(0.407)	(0.0380)	
3A	2	AWTR (odd)	= +0.0952	−0.00940		* +0.00011		+0.0564	−0.0000132	* −0.00364	−0.791	* +0.0516	0.04264
		s.d.	= (0.0416)	(0.00304)		(0.00224)		(0.0311)	(0.0000095)	(0.00416)	(0.559)	(0.0565)	
3B	3	AWTR (even)	= +0.0446	−0.00432		+0.00581		+0.0890	−0.0000152	−0.00843	−0.963	+0.1168	0.04349
		s.d.	= (0.0457)	(0.00199)		(0.00230)		(0.0296)	(0.0000086)	(0.00412)	(0.613)	(0.0515)	
4	1	AWTR	= +0.0909	−0.00524			* +0.00370	+0.0749	−0.0000165	−0.00403			0.04468
		s.d.	= (0.0310)	(0.00170)			(0.00467)	(0.0206)	(0.0000065)	(0.00295)			
5	1	AWTR	= +0.0755	−0.00560			+0.00894	+0.0651	−0.0000160	−0.00596	−1.034	+0.0857	0.04324
		s.d.	= (0.0306)	(0.00165)			(0.00478)	(0.0211)	(0.0000063)	(0.00291)	(0.407)	(0.0380)	
5A	2	AWTR (odd)	= +0.0950	−0.00939			* +0.00041	+0.0564	−0.0000133	* −0.00364	−0.793	* +0.0516	0.04264
		s.d.	= (0.0417)	(0.00303)			(0.00686)	(0.0311)	(0.0000095)	(0.00416)	(0.559)	(0.0565)	
5B	3	AWTR (even)	= +0.0442	−0.00434			+0.01774	+0.0891	−0.0000151	−0.00840	−0.961	+0.1167	0.04348
		s.d.	= (0.0458)	(0.00199)			(0.00700)	(0.0296)	(0.0000086)	(0.00413)	(0.613)	(0.0515)	

*Coef./s.d. ratio less than 1.0. Note 1, 175 cements, Avg. = 0.04066, S.D. = 0.04844 Note 2, 88 cements Note 3, 87 cements

TABLE 12–31. *Coefficients for equations for NAE cements relating the ratio of the difference between the percentage weight-loss on air drying and the percentage weight-gain with water storage divided by the percentage weight-loss of Series A concretes to various independent variables (AWTR = (AWET)/ADRY)*

Eq. No.	Note		Const.	Air content	C_3A	C_4AF	Fe_2O_3	Na_2O	APF	MgO	Cu	SrO	S.D.
1	1	AWTR	= +0.0544	−0.00718									0.04688
		s.d.	= (0.0074)	(0.00419)									
2	1	AWTR	= +0.0788	−0.00885	+0.00190	+0.00249		+0.0731	−0.0000197	−0.00379			0.04357
		s.d.	= (0.0378)	(0.00401)	(0.00131)	(0.00182)		(0.0207)	(0.0000066)	(0.00294)			
3	1	AWTR	= +0.0904	−0.00787		+0.00274		+0.0673	−0.0000191	−0.00527	−1.007	+0.0800	0.04239
		s.d.	= (0.0315)	(0.00394)		(0.00157)		(0.0210)	(0.0000064)	(0.00290)	(0.406)	(0.0392)	
3A	2	AWTR (odd)	= +0.1075	−0.01111		+0.00237		+0.0552	−0.0000201	* −0.00273	−1.248	* +0.0286	0.04252
		s.d.	= (0.0446)	(0.00613)		(0.00228)		(0.0313)	(0.0000100)	(0.00399)	(0.570)	(0.0540)	
3B	3	AWTR (even)	= +0.0838	* −0.00443		+0.00267		+0.0690	−0.0000196	−0.00795	−0.809	+0.1395	0.04323
		s.d.	= (0.0472)	(0.00538)		(0.00235)		(0.0306)	(0.0000089)	(0.00442)	(0.623)	(0.0590)	
4	1	AWTR	= +0.1082	−0.00891			* +0.00325	+0.0759	−0.0000201	−0.00325			0.04372
		s.d.	= (0.0318)	(0.00402)			(0.00463)	(0.0207)	(0.0000066)	(0.00292)			
5	1	AWTR	= +0.0900	−0.00788			+0.00844	+0.0673	−0.0000191	−0.00526	−1.009	+0.0800	0.04238
		s.d.	= (0.0315)	(0.00394)			(0.00478)	(0.0210)	(0.0000064)	(0.00290)	(0.406)	(0.0392)	
5A	2	AWTR (odd)	= +0.1074	−0.01111			+0.00727	+0.0551	−0.0000201	* −0.00271	−1.248	* +0.0287	0.04252
		s.d.	= (0.0447)	(0.00614)			(0.00696)	(0.0313)	(0.0000100)	(0.00399)	(0.570)	(0.0540)	
5B	3	AWTR (even)	= +0.0833	* −0.00444			+0.00827	+0.0691	−0.0000195	−0.00794	−0.814	+0.1394	0.04322
		s.d.	= (0.0473)	(0.00537)			(0.00715)	(0.0306)	(0.0000089)	(0.00443)	(0.623)	(0.0589)	

*Coef./s.d. ratio less than 1.0. Note 1, 163 cements, Avg. = 0.04329, S.D. = 0.04716 Note 2, 82 cements Note 3, 81 cements

TABLE 12–32. *Calculated contributions of independent variables to AWTR, the ratio of (ADRY – AWET)/ADRY for Series A concretes made of AE + NAE cements.*

Independent variable	Range of variables (percent)	Coefficients from eq 3 table 12–30	Calculated contributions to AWTR	Calculated range of contributions to AWTR
			Const. = +0.0758	
Air-content	0 to 13	–0.0056	0 to –0.073	0.073
C_4AF**	1 to 16	+0.00291	+0.003 to +0.047	0.044
Na_2O	0 to 0.7	+0.0651	0 to +0.046	0.046
APF	*2500 to 5500	–0.000016	–0.040 to –0.088	0.048
MgO	0 to 5	–0.00597	0 to –0.030	0.030
Cu	0 to 0.05	–1.032	0 to –0.051	0.051
SrO	0 to 0.4	+0.0857	0 to +0.034	0.034

*cm^2/g.
**Coefficient of doubtful significance as coef./s.d. ratio was less than 2.0.

TABLE 12–33. *"F" values for significance of reduction of variance due to added variables*

Table	Equations*	"F" ratio	D.F.	Critical "F" ratios α = 0.01	Critical "F" ratios α = 0.05
12–2	0,1	18.4	3:177	3.88	2.67
	1,2	24.0	5:172	3.13	2.28
	2,3	1.95	4:168	3.42	2.42
	0,4	17.4	5:175	3.13	2.28
	4,5	17.4	5:170	3.13	2.28
	5,6	3.27	3:167	3.88	2.67
12–3	0,1	17.8	3:165	3.88	2.67
	1,2	20.5	5:160	3.13	2.28
	2,3	2.07	3:157	3.90	2.67
	0,4	18.5	5:163	3.13	2.28
	4,5	12.9	5:158	3.13	2.28
	5,6	2.40	4:154	3.43	2.42
12–6	0,1	11.2	4:172	3.42	2.42
	1,2	26.6	4:168	3.42	2.42
	2,3	13.6	2:166	4.71	3.05
	3,4	2.56	4:162	3.43	2.42
	0,5	19.6	9:167	2.52	1.93
	5,6	13.5	2:165	4.73	3.05
	6,7	2.21	3:162	3.90	2.67
12–7	0,1	9.7	4:160	3.43	2.42
	1,2	23.9	4:156	3.43	2.42
	2,3	12.0	2:154	4.74	3.05
	3,4	2.20	4:150	3.44	2.42
	0,5	17.3	9:155	2.52	1.93
	5,6	11.9	2:153	4.74	3.05
	6,7	1.98	3:150	3.90	2.67
12–10	0,1	718	2:179	4.70	3.05
	0,2	6.77	2:179	4.70	3.05
	2,3	25.5	2:177	4.70	3.05
	3,4	34.2	4:173	3.42	2.42
	4,5	3.81	4:169	3.42	2.42
	0,6	19.1	6:175	2.92	2.15
	6,7	21.8	4:171	3.42	2.42
	7,8	4.31	4:167	3.42	2.42
12–11	0,1	816	2:167	4.72	3.05
	0,2	11.7	4:165	3.43	2.42
	2,3	31.4	4:161	3.43	2.42
	3,4	3.46	4:157	3.43	2.42
	0,5	14.5	6:163	2.92	2.15
	5,6	20.0	4:159	3.43	2.42
	6,7	3.81	4:155	3.44	2.42
12–14	0,1	2.65	2:173	4.73	3.05
	0,2	8.00	4:171	3.42	2.42
	2,3	26.4	4:167	3.43	2.42
	3,4	3.44	5:162	3.13	2.28
	4,5	4.05	1:161	6.77	3.90
	0,6	17.6	9:166	2.52	1.93
	6,7	3.94	4:162	3.44	2.42
	7,8	4.82	1:161	6.77	3.90
12–15	0,1	2.07	2:161	4.73	3.05
	0,2	7.16	4:159	3.44	2.42
	2,3	25.8	4:155	3.44	2.42
	3,4	3.27	5:150	3.14	2.28
	4,5	16.3	1:149	6.78	3.90
	0,6	16.7	9:154	2.52	1.93
	6,7	4.08	4:150	3.44	2.42
	7,8	16.9	1:149	6.78	3.90

TABLE 12–33. *"F" values for significance of reduction of variance due to added variables*—Continued

Table	Equations*	"F" ratio	D.F.	Critical "F" ratios α = 0.01	Critical "F" ratios α = 0.05
12–18	0,1	22.6	2:175	4.72	3.05
	1,2	13.0	6:169	2.92	2.15
	2,3	4.10	2:167	4.72	3.05
	0,4	17.7	8:169	2.62	2.00
	4,5	4.15	2:167	4.72	3.05
12–19	0,1	4.18	2:163	4.73	3.05
	1,2	12.3	6:157	2.92	2.15
	2,3	3.53	2:155	4.74	3.05
	0,4	10.7	8:157	2.62	2.00
	4,5	3.57	2:155	4.74	3.05
12–22	0,1	9.59	5:168	3.13	2.28
	1,2	2.81	5:163	3.13	2.28
	2,3	7.69	1:162	6.77	3.90
	0,4	8.11	6:167	2.92	2.15
	4,5	3.33	4:163	3.43	2.42
	5,6	7.69	1:162	6.77	3.90
12–23	0,1	5.76	5:156	3.14	2.28
	1,2	3.25	5:151	3.14	2.28
	2,3	6.87	1:150	6.78	3.90
	0,4	4.89	6:155	2.92	2.15
	4,5	3.93	4:151	3.44	2.42
	5,6	6.80	1:150	6.78	3.90
12–26	0,1	15.2	10:166	2.93	1.90
	1,2	4.50	2:164	4.72	3.05
	0,3	19.9	7:169	2.75	2.07
	3,4	3.40	2:167	4.72	3.05
12–27	0,1	8.70	10:154	2.93	1.90
	1,2	5.15	2:152	4.74	3.05
	0,3	10.4	7:157	2.75	2.07
	3,4	3.37	2:155	4.74	3.05
12–30	0,1	5.19	2:173	4.72	3.05
	1,2	5.44	5:168	3.13	2.28
	0,3	6.58	8:167	2.62	2.00
	0,4	6.12	6:169	2.92	2.15
	4,5	6.72	2:167	4.72	3.05
12–31	0,1	1.98	2:161	4.73	3.05
	1,2	6.08	5:156	3.13	2.28
	0,3	5.84	8:155	2.62	2.00
	0,4	5.44	6:157	2.92	2.15
	4,5	6.04	2:155	4.74	3.05

*0 in the equation column refers to the S.D. value of the corresponding dependent variable as given in footnotes in the tables of equations.

use of other commonly determined variables, C_3A, C_4AF, Na_2O, APF, and MgO, in eq 2 resulted in a further significant reduction in the S.D. value. The S.D. values of eqs 2 and 3 cannot be compared because of the absence of C_3A in eq 3, but, judging from eqs 4 and 5, it appears likely that the inclusions of Cu and SrO with the commonly determined variables caused a significant reduction of variance. (See table 12–33.)

The coef./s.d. for Fe_2O_3 in eq 4 was less than 1.0, but in eq 5 the ratio was greater than 1.0. In eqs 3A and 5A the coef./s.d. ratios for C_4AF, Fe_2O_3, MgO, and SrO were less than 1.0 with the smaller lot of cements.

A corresponding series of equations for the NAE cements is presented in table 12–31. The use of the air content in eq 1 did not result in a significant reduction of the S.D. value. (See table 12–33.) In eqs 3B and 5B the coef./s.d. ratio for the air-content of the NAE cements was less than 1.0 with the smaller groups of cement. The coefficients of the other independent variables were consistent with those of the previous table where the AE cements were included.

Using the coefficients of the independent variables of eq 3, table 12–30, and the ranges of these variables, computations were made of the calculated contributions to AWTR. These estimated contributions and the calculated ranges of the contributions are presented in table 12–32. Increases in air content and possibly fineness, MgO, and Cu were associated with decreases of the AWTR ratio. Increases of Na_2O and possibly SrO were associated with increases of the AWTR ratio.

TABLE 12–34. *Coefficients, coef./s.d. ratios, and calculated ranges of contributions to percentage loss of weight on drying, percentage gain of weight on resoaking, and ratios for Series O concretes made of NAE cements*

Column	1	2	3	4
Eq. No.	3	4	3	2
Table No.	12-3	12-11	12-19	12-27
Dependent variables	ODRY	OWET	ORWT	OWTR
Constant	+4.233	+3.813	+0.849	+0.189
Air content, coef.	+0.0846	+0.1128	+0.0124	−0.0136
Coef./s.d.	2.7	3.9	3.0	3.7
Calculated range	0.38	0.51	0.056	0.061
C_3A, coef.			−0.0020	+0.00223
Coef./s.d.			1.7	1.8
Calculated range			0.028	0.031
C_3S, coef.	−0.02265	−0.01931		−0.00101
Coef./s.d.	6.6	6.3		2.2
Calculated range	1.02	0.87		0.045
C_4AF, coef.	+0.03474	+0.03057	−0.00319	+0.00241
Coef./s.d.	3.6	3.3	2.0	1.6
Calculated range	0.49	0.43	0.045	0.034
Na_2O, coef.	−0.5362	−0.6766	−0.0653	+0.0408
Coef./s.d.	4.0	5.7	3.7	2.4
Calculated range	0.38	0.47	0.046	0.029
K_2O, coef.	−0.6471	−0.6138		
Coef./s.d.	5.6	5.8		
Calculated range	0.71	0.68		
SO_3, coef.	−0.2549	−0.1836		−0.0199
Coef./s.d.	3.8	3.0		2.1
Calculated range	0.51	0.36		0.040
MgO, coef.			+0.00611	−0.0068
Coef./s.d.			2.3	3.0
Calculated range			0.030	0.034
Loss, coef.	−0.0573	−0.0682	−0.0125	+0.0141
Coef./s.d.	1.3	1.8	2.1	2.6
Calculated range	0.17	0.20	0.038	0.042
APF, coef.			+0.0000429	−0.000026
Coef./s.d.			6.8	3.7
Calculated range			0.120	0.078
Ba, coef.	+0.923	+0.8131		
Coef./s.d.	1.5	1.4		
Calculated range	0.18	0.16		
Cu, coef.		+4.606	+0.665	−0.728
Coef./s.d.		2.0	1.8	2.3
Calculated range		0.23	0.33	0.036
Mn, coef.			−0.0441	
Coef./s.d.			1.8	
Calculated range			0.044	
Rb, coef.	−16.49	−19.28		
Coef./s.d.	1.3	1.8		
Calculated range	0.16	0.19		
SrO, coef.				−0.0727
Coef./s.d.				2.1
Calculated range				0.029
Zr, coef.	−0.657	−0.8397		
Coef./s.d.	1.2	1.8		
Calculated range	0.33	0.42		

6. Discussion

6.1. Variables Associated With Weight-Loss, Absorption, and Their Ratios

A series of equations selected from those previously given in tables for concretes made with NAE cements is presented in tables 12–34 and 12–35 in order that the variables, their coefficients, and the possible range of contributions to the dependent variables may be compared more readily. The equations are presented vertically instead of horizontally as in previous tables of this section. Reference is also made to the equations for the

TABLE 12–35. *Coefficients, coef./s.d. ratios, and calculated ranges of contributions to the percentage loss of weight on drying, the percentage gain of weight on resoaking, and ratios for Series A concretes made of NAE cements*

Column	1	2	3	4
Eq. No.	4	5	2	3
Table No.	12-7	12-15	12-23	12-31
Dependent variable	ADRY	AWET	ARWT	AWTR
Constant	−1.069	+0.560	+0.921	+0.0904
Air content, coef.	+0.0646		+0.00769	−0.00787
Coef./s.d.	1.9		1.8	2.0
Calculated range	0.29		0.035	0.035
w/c, coef.	+7.864	+5.047		
Coef./s.d.	4.8	4.1		
Calculated range	1.18	0.76		
C_3A, coef.	+0.02282	+0.01921		
Coef./s.d.	2.4	2.0		
Calculated range	0.32	0.27		
C_3S, coef.	−0.02216	−0.0190		
Coef./s.d.	6.7	5.8		
Calculated range	1.00	0.86		
C_4AF, coef.	+0.05101	+0.03078	−0.00273	+0.00274
Coef./s.d.	4.4	2.8	1.7	1.7
Calculated range	0.71	0.43	0.038	0.038
Na_2O, coef.	−0.5857	−0.7028	−0.0653	+0.0673
Coef./s.d.	4.6	5.7	3.1	3.2
Calculated range	0.41	0.49	0.046	0.047
K_2O, coef.	−0.6948	−0.6713		
Coef./s.d.	5.8	6.0		
Calculated range	0.76	0.74		
SO_3, coef.	−0.2511	−0.1648		
Coef./s.d.	3.5	2.4		
Calculated range	0.50	0.33		
MgO, coef.			+0.00509	−0.00527
Coef./s.d.			1.7	1.8
Calculated range			0.025	0.026
APF, coef.			+0.0000159	−0.0000191
Coef./s.d.			2.3	3.0
Calculated range			0.048	0.057
Loss, coef.	−0.0824	−0.0743		
Coef./s.d.	2.0	1.9		
Calculated range	0.25	0.22		
Ba, coef.	+1.043	+1.287	+0.190	
Coef./s.d.	1.7	2.1	1.7	
Calculated range	0.20	0.25	0.004	
Co, coef.		+19.71		
Coef./s.d.		1.3		
Calculated range		0.19		
Cu, coef.	+3.748	+6.973	+0.958	−1.007
Coef./s.d.	1.5	2.7	2.4	2.5
Calculated range	0.19	0.40	0.048	0.050
Rb, coef.	−12.31			
Coef./s.d.	1.0			
Calculated range	0.12			
SrO, coef.			−0.0865	+0.0800
Coef./s.d.			2.2	2.0
Calculated range			0.035	0.032
V, coef.			−0.306	
Coef./s.d.			1.5	
Calculated range			0.031	
Zr, coef.	−0.6953	−0.7586		
Coef./s.d.	1.3	1.6		
Calculated range	0.35	0.38		

concretes made of AE + NAE cements which have previously been presented.

The variables associated with the percentage loss of weight when the specimens were dried in air for 56 days (col 1) were generally, but with a few exceptions, also associated with the percentage weight-gain when the dried specimens were later placed in water for 28 days (col 2).

Higher air contents of the concretes were associated with higher values for weight-loss with air-drying and greater absorption on rewetting for the Series O concretes but not the Series A concretes. When the AE cements were included in the computation, the coef./s.d. ratio of the "air content" was greater. See eq 3 table 12–2 and eq 5 table 12–10.

Concretes made with NAE cements, which required a higher water/cement ratio to achieve the desired slump, also had higher weight-loss and absorption in drying and wetting, as shown by the coefficients for w/c in table 12–35, cols. 1 and 2.

Of the major potential compounds, higher C_3A was probably associated with higher loss on drying and gain on rewetting with the Series A concretes, but not with the Series O concretes. Higher

TABLE 12–36. *Relationships of weight loss and weight gain of concretes to dynamic Young's modulus of elasticity (in psi × 10^{-6}) of concretes at 14, 70, and 98 days*

Equation	Type cement		S.D.	"F"
1	AE+NAE	ODRY = +6.10 − 0.723 OD14 s.d. = (0.29) (0.060)	0.30	72
2		ODRY = +5.42 − 0.624 OD70 s.d. = (0.27) (0.060)	0.32	54
3		ODRY = +5.25 − 0.510 OD98 s.d. = (0.48) (0.095)	0.37	14.5
4		OWET = +6.26 − 0.775 OD14 s.d. = (0.24) (0.051)	0.26	114
5		OWET = +5.41 − 0.643 OD70 s.d. = (0.24) (0.054)	0.29	71
6		OWET = +5.76 − 0.628 OD98 s.d. = (0.43) (0.085)	0.33	27
7		ADRY = +6.12 − 0.720 AD14 s.d. = (0.37) (0.078)	0.33	43
8		ADRY = +5.27 − 0.583 AD70 s.d. = (0.33) (0.075)	0.34	30
9		ADRY = +4.64 − 0.384 AD98 s.d. = (0.62) (0.122)	0.39	5.00
10		AWET = +6.07 − 0.731 AD14 s.d. = (0.34) (0.071)	0.30	53
11		AWET = +5.16 − 0.580 AD70 s.d. = (0.31) (0.070)	0.32	35
12		AWET = +4.96 − 0.467 AD98 s.d. = (0.58) (0.131)	0.36	8.49
13	NAE	ODRY = +8.20 − 1.151 OD14 s.d. = (0.33) (0.067)	0.25	146
14		ODRY = +6.18 − 0.786 OD70 s.d. = (0.32) (0.070)	0.31	63
15		ODRY = +7.67 − 0.978 OD98 s.d. = (0.76) (0.148)	0.36	22
16		OWET = +7.72 − 1.074 OD14 s.d. = (0.30) (0.061)	0.23	152
17		OWET = +5.76 − 0.719 OD70 s.d. = (0.30) (0.065)	0.29	60
18		OWET = +7.23 − 0.913 OD98 s.d. = (0.70) (0.136)	0.22	22
19		ADRY = +8.01 − 1.103 AD14 s.d. = (0.35) (0.973)	0.26	115
20		ADRY = +6.00 − 0.738 AD70 s.d. = (0.34) (0.077)	0.32	46
21		ADRY = +6.79 − 0.798 AD98 s.d. = (0.74) (0.144)	0.37	15
22		AWET = +7.61 − 1.042 AD14 s.d. = (0.34) (0.072)	0.26	106
23		AWET = +5.71 − 0.699 AD70 s.d. = (0.33) (0.075)	0.32	44
24		AWET = +6.64 − 0.790 AD98 s.d. = (0.71) (0.138)	0.35	16

C_3S was associated with lower loss on drying and lower absorption when rewetted for both series. Higher C_4AF was associated with higher loss on drying and higher absorption for both series.

The coefficients for Na_2O and K_2O were highly significant in both drying and wetting for both series of concretes. Increases of the alkalies were associated with decreases of the loss of weight on drying and gain of weight on rewetting. Of the two alkalies, only Na_2O had a significant effect on the ratios ORWT and OWTR.

An increase of the SO_3 content in both series was associated with a decrease of the weight-loss or weight-gain but not with the ratios. However, an increase of fineness was not associated with the loss of weight or weight-regain when rewetted, but was associated with the ratios ORWT, OWTR, and AWTR.

Of the various trace elements, Cu had coef./s.d. values of 2.0 or greater with 5 of the 8 equations. SrO had coef./s.d. ratios of 2.0 or slightly over in some of the ratios (see columns 3 and 4 of tables 12–34 and 12–35.) Other trace elements usually had coef./s.d. values less than 2.0 and were, therefore, of doubtful significance.

6.2. Weight-Loss and Absorption Versus Dynamic Modulus of Elasticity

Table 12–36 shows linear equations indicating the relationship between the dynamic modulus of elasticity at 14, 70, and 98 days total age and the percentage loss of mositure during 56 days of drying and the percentage absorption with the subsequent 28 days in water. The independent variables, ODRY, OWET, ADRY, and AWET, as indicated previously are the weight-loss and weight-gain of the 6- × 8- × 16-in concrete blocks. The independent variables represent dynamic modulus values obtained from measurements of fundamental flexural frequencies of companion 3- × 4- × 16-in concrete beams made from the same concrete mixes as the blocks. OD14 and AD14 refer to the dynamic modulus after 14 days of moist curing; OD70 and AD70 to dynamic modulus of the same beams after 56 days of drying in laboratory air (total age 70 days); and OD98 and AD98 to dynamic modulus after 28 days soaking in water (total age 98 days). The initial O and A, respectively, refer, as with other symbols, to the Series O concretes with constant w/c ratio and Series A concretes with constant slump.

The reduction of variance was greater when the loss or gain of weight was related to the values for dynamic modulus after 14 days moist curing. This was found for both the Series O and Series A concretes each made of AE + NAE or NAE cements. Higher dynamic modulus was significantly related at all ages and conditions of test to lower loss of weight with drying and lower absorption when rewetting.

6.3. Air Content Versus Absorption and Weight-Loss

As indicated in subsection 6.1 as well as in the various equations of this section, higher air contents of the concretes were associated with higher weight-loss on drying and higher weight-gain when placed in water. It was previously indicated in section 10, tables 10–1 and 10–2, and in the discussion in subsection 6.1 of section 10 that concretes made with air-entraining cements had lower cement contents than the original design mix and most of the concretes made with non-air-entraining cements. The somewhat leaner and more porous nature of the concretes made with the air-entraining cements may therefore have been responsible for the higher weight-loss and absorption. However, as indicated in section 11 on durability in subsection 6.3, the saturation ratio after 24 hours in water was lower with higher air contents. The longer period (28 days versus 24 hours) in water may also have been responsible for the differences in these two series of tests.

7. Summary and Conclusions

Concrete specimens 6- × 8- × 16-in (approx. 15- × 20- × 40-cm) were made from 199 portland cements of different types, using 5½ bags of cement per cubic yard (approx. 307 kg/m^3). In one series, the water-cement ratio was constant at 0.635, and in the other, the water was adjusted, if necessary, to obtain a slump of 5 ± 1 in (12.7 ± 2.5 cm). Specimens were moist cured for 14 days, dried in laboratory air for 56 days, and then immersed in water for 26 days. Determinations were made of the percentage weight-loss and the percentage absorption, and various ratios were calculated for the weight-loss and weight-gain. The observations and conclusions were as follows:

(7.1) The percentage loss of weight as a result of drying in laboratory air ranged from less than 2.0 to more than 4.0 percent.

(7.2) When the air-dried specimens were later immersed in water for 28 days the absorption ranged from less than 2.0 up to 4.0 percent. There was a highly significant relationship between the loss on drying and the subsequent absorption.

(7.3) The ratio of weight-gain to weight-loss ranged from about 0.8 to 1.2 and the ratio of (ODRY−OWET)/ODRY ranged from about −0.15 to +0.18 with similar values for the A Series.

(7.4) The frequency distributions of the weight-loss, weight-gain, and the two ratios indicated that a range of values was obtained for each of the types of cement, and that there was considerable overlapping of the values obtained for the different types.

(7.5) Computations of equations by a least-

squares method were used to determine the chemical and physical properties of the cements which were associated with the weight-loss, the weight-gain, and the ratios of gain to loss. The equations were computed for all cements for which minor constituents and trace elements had been determined. Equations were computed for the AE + NAE cements and for the NAE cements. The equations were computed using the calculated major potential compounds or the major oxides together with other commonly determined variables, and then with trace elements which appeared to have a significant effect.

The following observations relate to the Series O concretes made of NAE cements as summarized in table 12–34:

(7.5.1) Increases of C_4AF and possibly air content were associated with increases of ODRY, the percentage loss of weight on drying. Increases of C_3S, Na_2O, K_2O, and SO_3 were associated with decreases of the loss of weight on drying.

(7.5.2) Increases of the air content, C_4AF, and possibly Cu were associated with increases of OWET, the percentage weight-gain when the air-dried specimens were immersed in water for 28 days. Increases of C_3S, Na_2O, K_2O, and SO_3 were associated with decreases of the weight-gain.

(7.5.3) Increases of air content and fineness, and possibly MgO, were associated with increases of ORWT, the ratio OWET/ODRY. Increases of Na_2O, and possibly C_4AF and Loss, were associated with decreases of ORWT. Of these, variations of fineness had the greatest calculated effect.

(7.5.4) Increases of air content, fineness, MgO, and possibly C_3S, Cu, and SrO, were associated with decreases of OWTR, the ratio (ODRY −OWET)/ODRY. Increases of Na_2O and loss on ignition were possibly associated with increases of the OWTR ratio.

(7.6) The independent variables associated with the dependent variables of the Series A concretes (where the water was adjusted to obtain a selected slump) were in general agreement with those of the constant water/cement ratio concretes.

(7.7) The use of the major oxides instead of the calculated potential compounds as independent variables (together with other commonly determined variables) resulted in equations with similar estimated standard deviation values.

(7.8) Of the various trace elements, the coefficients for Cu and SrO were probably significant in equations for some of the properties. Other trace elements, though appearing in the equations, were of doubtful significance.

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Section 13. Dynamic Young's Modulus of Elasticity of Concrete

R. L. Blaine and H. T. Arni

The relationships between cement characteristics and dynamic Young's modulus of elasticity of concretes at different ages and moisture conditions were studied by computing multivariable regression equations with the aid of a digital computer. An increase of the air-content and water/cement ratio needed for the desired slump were associated with a decrease of the dynamic E. Increases in C_3S and SO_3 were associated with increases of the dynamic E. Other independent variables, although significant, generally had less effect on the dynamic E. The use of trace elements as independent variables in equations resulted in a significant reduction of variance when the concrete specimens were moist. There was generally a decrease of dynamic modulus when moist specimens were dried in laboratory air for 4 or 8 weeks and an increase when the air-dried specimens were resaturated. Placing the air-dried specimens in water for 24 hours resulted in a slight decrease in dynamic modulus with some concretes and an increase with other concretes.

Key words: Cement composition; compressive strength; concrete; dynamic modulus of elasticity; effect of moisture on dynamic E; modulus of rupture; portland cement; trace elements.

Contents

1. Introduction

Modulus of elasticity determined by resonant frequency methods has been used to study the effects on concrete properties of various treatments, conditions, or changes in conditions [1, 2, 3, 4].[1] Examples of such use include: (1) deterioration due to freezing and thawing in laboratory tests [5, 6]; (2) deterioration due to natural weathering [7]; (3) effect of chemical attack [8]; (4) effects of incomplete consolidation [9]; (5) effect of curing methods [10]. Also various studies have been made in an attempt to relate dynamic modulus to other properties of the concrete such as static modulus of elasticity, creep, relaxation,

[1] Figures in brackets refer to literature references at the end of this section (p. 125).

shrinkage, and compressive, flexural, and tensile strength [11, 12, 13, 14].

The object of this paper is to investigate the effect on dynamic modulus under various conditions of curing, drying, and rewetting of variables connected with the cements used. The source and amount of aggregate was the same throughout the study. The cement content was held constant, except for changes required by the amount of entrained air. Dynamic modulus tests were conducted according to ASTM Designation C 215 [15].

2. Materials

2.1. Cements

The cements used in the present tests were the same as those used in the work reported throughout the series of sections of the Interrelation Between Cement and Concrete Properties. The results of chemical analyses and the semiquantitative spectrochemical analyses were presented in sections 2 and 3 of part 1 of this series of articles [16]. Reports of other properties of these cements, mortars, and concretes have been presented in parts 2, 3, 4 [17, 18, 19], and in the first two sections of the present part 5. Most of the 199 portland cements were obtained from different areas of the United States, but a few were obtained from other countries.

2.2. Aggregates

A high quality rounded quartzite coarse aggregate was used with a sand from the same source. The sand and coarse aggregate gradation was previously presented in section 1 [16].

3. Methods of Test

3.1. Preparation of Concretes

The details of the proportioning and mixing of the concretes were described in part 1, section 1 of this series of articles [16]. Two series of concretes were made with these cements; one (Series O) was made using a water/cement (w/c) ratio of 0.635, and the other (Series A) with the water varied, if necessary, to give a concrete with a 5 ± 1-in slump. The concrete mix was designed to contain 5.5 bags of cement per cubic yard but varied somewhat as indicated in section 11 because of the amount of entrained air.

3.2. Test Specimens

The 3- × 4- × 16-in concrete specimens of the two series were made from the same batches of concrete used for the shrinkage and expansion tests [19], the durability tests, and the weight-loss and weight-gain tests reported in sections 11 and 12 of this publication.

3.3. Storage of Test Specimens

The concrete was cured at 73 ± 1 °F in the molds under damp burlap for the first 20 to 24 hours, then placed in a fog room at 100 percent relative humidity until 14 days old. The specimens were then placed on end and exposed to laboratory air at 73 °F and 50 percent relative humidity for 8 weeks. The specimens were then placed in water for an additional 4 weeks.

3.4. Measurements of Specimens

The fundamental transverse frequencies of the concrete specimens were determined in accordance with ASTM Method C 215 [15]. The measurements were made on two 3- × 4- × 16-in prisms of each of the two series of concretes at 14 days (after moist curing), at 70 days (after 8 weeks of drying in laboratory air), at 71 days (after 24 hours in water), and at 98 days (after 4 weeks in water).

4. Abbreviations

The abbreviations, notations, etc., used in this section for physical and chemical properties of the cements are the same as those used in previous sections of this series of articles.[2]

In this section, as in the previous three, the prefix "O" of the four-letter titles for the various dependent variables refers to the concretes of Series O in which a water/cement (w/c) ratio of 0.635 was used. The prefix A refers to the Series A concretes which had a 5 ± 1-in slump. A summary of other titles for the dependent variables used in this section are as follows:

For Series O concretes made with a w/c of 0.635

OD14 = dynamic modulus in psi $\times 10^{-6}$ at 14 days after moist curing.

OD42 = dynamic modulus in psi $\times 10^{-6}$ after 14 days moist curing followed by 28 days drying in laboratory air.

OD70 = dynamic modulus in psi $\times 10^{-6}$ after 14 days moist curing followed by 56 days drying in laboratory air.

[2] These abbreviations include the use of C_3A, C_3S, C_2S, and C_4AF for the calculated potential compounds, tricalcium aluminate, tricalcium silicate, dicalcium silicate, and tetracalcium aluminoferrite, respectively. Also used are Insol for insoluble residue, Loss for loss on ignition, APF for air permeability fineness, Wagn for Wagner Turbidimeter fineness. AE + NAE refers to air-entraining plus non-air-entraining cements, and NAE to the non-air-entraining cements.

OD71 = dynamic modulus in psi $\times 10^{-6}$ after air dried specimens had been placed in water for 24 hours.

OD98 = dynamic modulus in psi $\times 10^{-6}$ after air dried specimens had been in water for 28 days.

OE 70/14 = OD70/OD14

OE 98/70 = OD98/OD70

OE 71/70 = OD71/OD70

For Series A concretes having a 5 ± 1-in slump, the letter "A" is used instead of "O", as AD14, AD42, AD70, AD71, AD98, AE 70/14, AE 98/70, and AE 71/70 for the different independent variables.

The values for dynamic Young's modulus of elasticity will generally be referred to as dynamic modulus, or dynamic E.

5. Statistical Analyses

The statistical techniques used to find and evaluate the independent variables associated with the dynamic modulus at the various ages and test conditions and the ratios of these values have been described in a previous section of this series part 1, section 1, Materials and Techniques [16]. The statistical treatment was the same as that used in all previous sections of this series of articles. Multiple regression equations were calculated by a least-squares method using various independent variables to determine which showed an association with each of the dependent variables. As in previous sections, equations were calculated for both the AE + NAE cements and the NAE cements. Calculations were made using only commonly determined variables and also using these together with minor and trace elements.

After equations had been developed in which independent variables showed significant relationships with the dependent variable, the residuals of these equations were fitted by a least-squares method to other independent variables and the reduction in variance calculated. If any of the additional independent variables indicated a significant reduction in variance, they were tried in the equation and retained if the coef./s.d. ratio was greater than 1.0.[3]

Ratios of reduction in variance to original variance ("F" ratios) obtained by fitting equations were calculated for two kinds of cases: (1) for equations including a few main independent variables as compared to the original data on the dependent variable, or (2) for equations in which additional independent variables were included as compared to a previous equation with fewer variables. The calculated "F" ratios and the critical "F" values which must be equaled or exceeded for significance at the $\alpha = 0.05$ and $\alpha = 0.01$ levels are summarized in a table (table 13–57).

Equations were also calculated for the "odds" and "evens" in the array of cements. Comparisons were made of the coefficients of the variables in the two groups of data and these were compared to the coefficients and coef./s.d. ratios computed for all the cements.

Although dynamic modulus of elasticity was determined for both series of concretes made of all of the 199 cements, the calculations of equations presented in this section were limited to those cements for which trace-element determinations had been made.

Equations presented in this section were selected from a large number of trial equations indicating the calculated relationship of various variables to the dynamic modulus values or their ratios.[4] A summary of the relationships indicated by the equations for both series of concretes is given in the discussion in subsection 7.

Some of the limitations on interpretation of multivariable regression equations as well as other statistical techniques used in this series of articles have been discussed in section 1, subsections 4.2, 4.3, and 5 [16]. Other limitations and problems of interpretation have also been discussed in other sections of this series of articles.

[3] Statistical terms and notations employed in this section are the same as those used in previous sections of this series of articles. For example, S.D. refers to the estimated standard deviation calculated from the residuals of a fitted equation, or the estimated standard deviation about the average. Also, as in previous sections, s.d. refers to the estimated standard deviation of a coefficient of an independent variable used in a fitted equation. The term coef./s.d. is the ratio of the estimated coefficient (of an independent variable used in an equation) to its estimated standard deviation. "F" designates Fisher's ratio of variances and D.F. is used to designate the number of degrees of freedom. As indicated in previous sections, a coef./s.d. ratio greater than 1.0 was considered to be of sufficient significance to warrant further investigation.

[4] These equations were selected primarily to indicate the association with commonly determined independent variables having coef./s.d. ratios greater than 1.0 when used in multivariable equations, and also to indicate which of minor and trace elements may show a significant relationship.

6. Results of Tests

6.1. Dynamic Modulus After 14 Days Moist Curing

6.1.1. Dynamic Modulus of Series O Concretes

The frequency distribution of the dynamic moduli of the Series O concretes after 14 days moist curing is presented in table 13–1. There was a broad distribution of values and an overlapping of the values for the different types of cement. The air-entraining cements (Types IA, IIA, and IIIA) generally had values in the lower half of the distribution curve.

Equations are presented in table 13–2 indicating the variables associated with the dynamic modulus of Series O concretes made of AE + NAE

TABLE 13–1. *Frequency distribution of cements with respect to OD14, the dynamic modulus of elasticity of Series O concretes after 14 days moist curing*

Type cement	Dynamic modulus of elasticity, 10^6 psi											
	3.4 to 3.6	3.6 to 3.8	3.8 to 4.0	4.0 to 4.2	4.2 to 4.4	4.4 to 4.6	4.6 to 4.8	4.8 to 5.0	5.0 to 5.2	5.2 to 5.4	5.4 to 5.6	Total
	Number of cements											
I					1	3	16	34	24	3	1	82
IA	2	3	3									8
II			1	1	1	13	17	25	9	1		68
IIA		1			1	1						3
III							2	4	10	4		20
IIIA			1		1		1					3
IV, V	1		2		4	2	3	2	1			15
Total	3	4	7	1	8	19	39	65	44	8	1	199

TABLE 13–2. *Coefficients for equations relating OD14, the dynamic Young's modulus of NAE cements, to various*

Eq. No.	Note	10^6 psi	Const.	Air content	C_3A	C_3S	C_4AF	CaO	SiO_2
1	1	OD14 s.d.	= +3.767 = (0.173)	−0.1622 (0.0078)	+0.00965 (0.00585)	+0.0194 (0.0022)	−0.0196 (0.0075)		
2	1	OD14 s.d.	= +3.723 = (0.170)	−0.1593 (0.0077)	+0.01007 (0.00584)	+0.0196 (0.0021)	−0.0178 (0.0074)		
2A	2	OD14 (odd) s.d.	= +3.718 = (0.248)	−0.1562 (0.0108)	* +0.00332 (0.00850)	+0.0193 (0.0028)	−0.0236 (0.0106)		
2B	2	OD14 (even) s.d.	= +3.811 = (0.249)	−0.1646 (0.0116)	+0.01558 (0.00852)	+0.0190 (0.0036)	−0.0124 (0.0109)		
3	1	OD14 s.d.	= +1.978 = (2.492)	−0.1621 (0.0078)				+0.0975 (0.0272)	−0.1306 (0.0288)
4	1	OD14 s.d.	= +1.681 = (2.504)	−0.1592 (0.0077)				+0.1009 (0.0274)	−0.1298 (0.0285)
4A	2	OD14 (odd) s.d.	= +1.615 = (3.817)	−0.1562 (0.0109)				+0.1003 (0.0411)	−0.1267 (0.0418)
4B	2	OD14 (even) s.d.	= +0.735 = (3.621)	−0.1643 (0.0116)				+0.1093 (0.0403)	−0.1164 (0.0433)

*Coef./s.d. ratio less than one.

Note 1, 180 cements, Avg. = 4.75 × 10^6 psi, S.D. = 0.3550 × 10^6 psi
Note 2, 90 cements

TABLE 13–3. *Coefficients for equations relating OD14, the dynamic Young's modulus cements, to various*

Eq. No.	Note	10^6 psi	Const.	Air content	C_3A	C_3S	C_4AF	CaO	SiO_2
1	1	OD14 s.d.	= +3.691 = (0.171)	−0.1328 (0.0195)	+0.00947 (0.00590)	+0.0193 (0.0022)	−0.0168 (0.0075)		
2	1	OD14 s.d.	= +3.618 = (0.176)	−0.1346 (0.0193)	+0.01056 (0.00596)	+0.0197 (0.0022)	−0.0144 (0.0075)		
2A	2	OD14 (odd) s.d.	= +3.634 = (0.262)	−0.1344 (0.0321)	+0.01025 (0.00946)	+0.0197 (0.0030)	* −0.0096 (0.0127)		
2B	2	OD14 (even) s.d.	= +3.603 = (0.258)	−0.1369 (0.0252)	+0.01004 (0.00824)	+0.0193 (0.0036)	−0.0193 (0.0099)		
3	1	OD14 s.d.	= +4.377 = (1.174)	−0.1321 (0.0196)				+0.0721 (0.0141)	−0.155 (0.022)
4	1	OD14 s.d.	= +2.249 = (2.593)	−0.1348 (0.0194)				+0.0947 (0.0284)	−0.137 (0.029)
4A	2	OD14 (odd) s.d.	= +4.213 = (4.480)	−0.1351 (0.0316)				+0.1621 (0.0483)	−0.077 (0.047)
4B	2	OD14 (even) s.d.	= +4.081 = (3.414)	−0.1367 (0.0254)				+0.0737 (0.0386)	−0.151 (0.041)

*Coef./s.d. ratio less than one.

Note 1, 168 cements, Avg. = 4.820 × 10^6 psi, S.D. = 0.2585 × 10^6 psi
Note 2, 84 cements

cements. The use of commonly determined variables, air content, C_3A, C_3S, C_4AF, SO_3, Na_2O, K_2O, and MgO in eq 1 resulted in a highly significant reduction in variance. (See table 13–57,[5] p. 108).

Using these commonly determined variables in eq 2 together with the trace elements Mn, Rb, and Zr which had coef./s.d. ratios greater than 1.0, a further significant reduction in variance was obtained. Equations 2A and 2B, calculated for the "odds" and "evens" in the array of cements indicated that C_3A, Na_2O, MgO, and Mn had coef./s.d. ratios less than 1.0 in one or the other of the smaller groups of cements.[6]

The major oxides CaO, SiO_2, Al_2O_3, and Fe_2O_3 were used in eq 3 instead of the calculated potential compounds as in eqs 1 and 2. There was a significant reduction in variance, and when the trace elements Mn, Rb, and Zr were used with the commonly determined variables in eq 4 there was a further reduction in variance. (See table 13–57.)

In eqs 4A and 4B calculated for the "odds" and

[5] A tabulation of the "F" values for reduction in variance for all equations compared is presented in table 13–57. Presented also are the critical values for "F" which must be equaled or exceeded for significance at the 1- and 5-percent levels for the number of degrees of freedom (D.F.) involved in each comparison.

[6] As has been indicated in previous sections of this series of articles, this may occur if a number of cements having higher than normal values for an independent variable are included in one of the two groups. If the coefficients of a variable in smaller groups, i.e. the odds and evens, both are significant, a greater confidence can be placed on the significance of the variable of the equation where all cements were included.

elasticity in 10^6 psi after 14 days moist curing of Series O concretes made of AE + independent variables

Al_2O_3	Fe_2O_3	SO_3	Na_2O	K_2O	MgO	Mn	Rb	Zr	S.D.
------------	------------	+0.146 (0.042)	+0.302 (0.083)	+0.240 (0.071)	+0.0138 (0.0123)	------------	------------	------------	0.1763
------------	------------	+0.160 (0.041)	+0.260 (0.082)	+0.148 (0.078)	+0.0240 (0.0125)	−1.188 (0.115)	+18.63 (7.76)	+0.561 (0.331)	0.1718
------------	------------	+0.237 (0.057)	+0.272 (0.105)	+0.124 (0.110)	*+0.0130 (0.0180)	*−0.052 (0.154)	+14.92 (9.92)	+1.675 (0.853)	0.1678
------------	------------	+0.079 (0.062)	*+0.116 (0.157)	+0.205 (0.121)	+0.0369 (0.0178)	−0.445 (0.181)	+19.82 (12.90)	+0.488 (0.383)	0.1762
−0.0875 (0.0319)	−0.0867 (0.0299)	+0.117 (0.057)	+0.315 (0.085)	+0.253 (0.073)	+0.0298 (0.0257)	------------	------------	------------	0.1765
−0.0855 (0.0317)	−0.0799 (0.0296)	+0.135 (0.057)	+0.273 (0.084)	+0.166 (0.081)	+0.0422 (0.0257)	−0.176 (0.116)	+18.39 (7.77)	+0.617 (0.339)	0.1720
−0.1022 (0.0433)	−0.0856 (0.0440)	+0.215 (0.085)	+0.284 (0.108)	+0.150 (0.120)	*+0.0296 (0.0354)	*−0.042 (0.156)	+14.57 (9.97)	+1.795 (0.881)	0.1684
−0.0562 (0.0508)	−0.0618 (0.0434)	*+0.070 (0.085)	*+0.140 (0.160)	+0.217 (0.122)	+0.0673 (0.0402)	−0.416 (0.185)	+19.91 (12.93)	+0.555 (0.392)	0.1765

of elasticity in 10^6 psi after 14 days moist curing of Series O concretes made of NAE independent variables

Al_2O_3	Fe_2O_3	SO_3	Na_2O	K_2O	MgO	Mn	Rb	Zr	S.D.
------------	------------	+0.165 (0.042)	+0.300 (0.084)	+0.252 (0.071)	------------	------------	------------	------------	0.1738
------------	------------	+0.177 (0.041)	+0.257 (0.085)	+0.152 (0.081)	+0.0204 (0.0126)	−0.183 (0.119)	+15.39 (7.91)	+0.580 (0.332)	0.1704
------------	------------	+0.178 (0.060)	+0.212 (0.109)	*+0.112 (0.125)	*+0.0132 (0.0180)	−0.415 (0.164)	+25.07 (11.53)	*+0.586 (2.245)	0.1727
------------	------------	+0.203 (0.063)	+0.335 (0.148)	+0.119 (0.115)	+0.0274 (0.0186)	+0.193 (0.191)	*+3.98 (12.11)	+0.526 (0.362)	0.1691
−0.112 (0.025)	−0.101 (0.021)	+0.097 (0.048)	+0.295 (0.085)	+0.236 (0.076)	------------	------------	------------	------------	0.1741
−0.092 (0.033)	−0.077 (0.030)	+0.141 (0.058)	+0.266 (0.087)	+0.166 (0.085)	+0.0326 (0.0266)	−0.179 (0.121)	+15.26 (7.92)	+0.619 (0.340)	0.1707
*−0.035 (0.050)	*+0.007 (0.055)	+0.236 (0.090)	+0.276 (0.113)	+0.191 (0.131)	+0.0835 (0.0439)	−0.401 (0.162)	+25.10 (11.37)	*−0.380 (2.281)	0.1702
−0.108 (0.048)	−0.108 (0.039)	+0.141 (0.083)	+0.333 (0.149)	+0.118 (0.117)	*+0.0228 (0.0362)	*+0.187 (0.200)	*+3.85 (12.21)	+0.511 (0.381)	0.1702

"evens" in the array of cements, the variables SO_3, Na_2O, MgO, and Mn had coef./s.d. ratios less than 1.0 in one or the other of the equations for the smaller groups of cements.

A similar series of equations is presented in table 13–3 for the Series O concretes made with NAE cements. The coefficients for the air content were highly significant even with the concretes made with non-air-entraining cements. The coefficients of the other variables, the coef./s.d. ratios, and S.D. values were in reasonable agreement with those of table 13–2 where the air-entraining cements were included. Including the trace elements in eqs 2 and 4 together with commonly determined variables resulted in a reduction of variance significant at the $\alpha = 0.05$ level. In eqs 2A, 2B, 4A, and 4B calculated for the "odds" and "evens" the coef./s.d. ratio of C_4AF, Al_2O_3, Fe_2O_3, K_2O, MgO, Mn, Rb, and Zr was less than 1.0 in one or the other of the equations for the smaller groups of cements.

Using the independent variables of eq 2, table 13–3, and the ranges of these variables, values were calculated for their contributions and ranges of contributions to the dynamic modulus after 14 days moist curing. These calculated values, as presented in table 13–4, are approximations based on a single equation, and somewhat different values would be obtained by the use of other equations.[7]

Table 13–4. *Calculated contributions of independent variables to OD14, the 14-day dynamic modulus of Series O concretes*

Independent variable	Range of variables (percent)	Coefficients from eq 2 table 13–3	Calculated contributions to OD14	Calculated range of contributions to OD14
			Const. = +3.62	
Air-content, NAE cements	0 to 4.5	−0.1346	0 to −0.61	0.61
C_3A*	1 to 15	+0.01056	+0.01 to +0.15	0.14
C_3S	20 to 65	+0.0197	+0.39 to +1.28	0.89
C_4AF*	1 to 16	−0.0144	−0.01 to −0.23	0.22
SO_3	1.2 to 3.0	+0.177	+0.21 to +0.53	0.32
Na_2O	0 to 0.7	+0.257	0 to +0.17	0.17
K_2O*	0 to 1.1	+0.152	0 to +0.17	0.17
MgO*	0 to 5	+0.0204	0 to +0.10	0.10
Mn*	0 to 1.0	−0.183	0 to −0.18	0.18
Rb*	0 to 0.01	+15.39	0 to +0.15	0.15
Zr*	0 to 0.5	+0.580	0 to +0.29	0.29

*Coefficient of doubtful significance as coef./s.d. ratio was less than 2.

Increases in air content were associated with decreases in the dynamic modulus values. Increases of C_3S, SO_3, and Na_2O were associated with increases of dynamic modulus. Differences in the air content and C_3S had the greatest calculated contribution to the 14-day dynamic modulus as determined from this equation.

6.1.2. Dynamic Modulus of Series A Concretes

The frequency distribution of the dynamic modulus of the Series A concretes is presented in table 13–5. There was a broad distribution of values and an overlapping of the values for the different types of cement. The majority of the concretes made of the air-entraining cements, as with the Series O concretes (table 13–1), had lower values for dynamic modulus than the over-all average.

A series of equations is presented in table 13–6 to indicate the relationship of various independent variables to the dynamic modulus of Series A concretes made of AE + NAE cements. The use of the air content as an independent variable in eq 1, or w/c in eq 2 or both in eq 3 resulted in a significant reduction in variance. (See table 13–57). The additional use of the commonly determined variables C_3S, C_4AF, SO_3, Na_2O, K_2O, and MgO in eq 4 resulted in a highly significant reduction in variance. The coefficient for w/c was greater in magnitude and had a higher coef./s.d. ratio in eq 4 than in eq 3. It was indicated in a previous section [16] that a number of independent variables was related to the water requirement of the cements, and it may be that the differences in these coefficients indicate some interaction between water/cement ratio and other independent variables.

With the use of the commonly determined variables together with the trace elements Rb and Mn in eq 5 there was a reduction in variance

[7] Computations for contributions to dynamic modulus at other ages have been made from similar equations, i.e., one selected from the NAE cements containing one or more of the potential major compounds, other commonly determined variables, and trace elements in order that the trends may be followed more easily.

Table 13–5. *Frequency distribution of cements with respect to AD14, the dynamic modulus of elasticity of Series A concretes after 14 days moist curing*

Type cement	Dynamic modulus of elasticity, psi $\times 10^{-6}$											
	3.6 to 3.8	3.8 to 4.0	4.0 to 4.2	4.2 to 4.4	4.4 to 4.6	4.6 to 4.8	4.8 to 5.0	5.0 to 5.2	5.2 to 5.4	5.4 to 5.6	5.6 to 5.8	Total
	Number of cements											
I	-------	-------	-------	3	6	20	32	14	1	2	1	79
IA	-------	1	4	3	-------	-------	-------	-------	-------	-------	-------	8
II	-------	-------	2	4	8	21	23	8	1	-------	-------	67
IIA	1	-------	-------	-------	1	1	-------	-------	-------	-------	-------	3
III	-------	-------	-------	-------	-------	1	5	11	2	1	-------	20
IIIA	-------	-------	-------	-------	2	-------	1	-------	-------	-------	-------	3
IV, V	1	1	1	2	6	2	1	1	-------	-------	-------	15
Total	2	2	7	12	23	45	62	34	4	3	1	195

significant at the $\alpha = 0.05$ level. (See table 13–57.) The coef./s.d. ratios of Na_2O, Rb, and Mn were less than 1.0 in eqs 5A or 5B calculated for the "odds" and "evens" in the array of cements.

The use of the major oxides in eq 6 together with other commonly determined variables resulted in an S.D. value not significantly different from that of eq 4 where the potential compounds were used as independent variables. The additional use of the independent variables MgO, Rb, and Mn in eq 7 did not result in a reduction of variance significant at the $\alpha = 0.05$ level. The eqs 7A and 7B calculated for the "odds" and "evens" in the array of cements indicated that CaO, SO_3, Na_2O, K_2O, MgO, and Rb had coef./s.d. ratios of less than 1.0 in one or the other or both of the equations for the smaller group of cements.

An analogous series of equations calculated for the dynamic modulus after 14 days moist curing of Series A concretes made with NAE cements is presented in table 13–7. As indicated in eqs 1, 2, and 3, the coefficients for air content and w/c were not significant. In eqs 4 through 7 the coefficients for air content and w/c were highly significant when used together with other independent variables. Increases in both air content and w/c were associated with decrease in the dynamic modulus. The use of the commonly determined variables in eqs 4 and 6 resulted in a highly significant reduction in variance. The additional use of the trace elements Rb, Mn, and Cu in eqs 5 and 7 resulted in a reduction in variance significant at the 5.0-percent level in eq 7 but not in eq 5. (See table 13–57.)

In equations calculated for the "odds" and "evens" in the array of cement (eqs 5A, 5B, 7A, and 7B) there were instances where the coef./s.d. ratios of SO_3, Na_2O, K_2O, MgO, Rb, Mn, and Cu were less than 1.0 in one or the other or both of the equations for the smaller groups of cement.

Using the independent variables of eq 5 table 13–7 and the ranges of these variables, values were calculated for their contributions and ranges of contributions to the dynamic modulus after 14 days moist curing. These calculated values are presented in table 13–8. Increases of air content, w/c, C_4AF and Mn were associated with decreases of the dynamic modulus values. Increases of C_3S, SO_3, Na_2O, K_2O were associated with increases of the dynamic modulus. Of these variables, differences of air content, w/c, and C_3S showed the greatest calculated contribution.

6.2. Dynamic Modulus After 28 Days Drying

6.2.1. Dynamic Modulus of Series O Concretes

The frequency distribution of the dynamic modulus after 28 days drying for the Series O concretes is presented in table 13–9. The concrete specimens were moist cured for 14 days and then dried in laboratory air for 28 days. There was a broad distribution of results and an overlapping of the values for the concretes made of the different types of cement.

Variables associated with the dynamic modulus after 28 days drying of the Series O concrete made of AE + NAE cements are presented in table 13–10. The use of the independent variables, air content, C_3A, C_3S, C_4AF, SO_3, Na_2O, APF, and MgO in eq 1 resulted in a highly significant reduction in variance. (See table 13–57.) As indicated in eq 2, Cu was the only trace element having a coef./s.d. ratio greater than 1.0 when used as an independent variable together with commonly determined variables. The reduction in variance was not significant at the 5.0-percent level.

Equations 2A and 2B indicate that C_3A, fineness, and Cu had coef./s.d. ratios of less than 1.0 in one of the equations for the smaller groups of cements.

The use of SiO_2, Al_2O_3, and Fe_2O_3 together with other commonly determined variables in eq 3 resulted in a significant reduction in variance (See table 13–57) but the additional use of Cu in eq 4 did not result in a reduction of variance significant at the 5.0-percent level. In equations for the "odds" and "evens," 4A and 4B, the coef./s.d. ratios of Na_2O and Cu were less than 1.0 in one or the other of the equations for the smaller groups of cement.

A similar series of equations for the NAE cements is presented in table 13–11. The coefficients of the independent variables, the coef./s.d. ratios, and the S.D. values obtained were in reasonable agreement with the preceding table where the AE cements were included.

Using the independent variables of eq 2, table 13–11, and the ranges of these variables, calculations were made of the estimated contributions and ranges of contributions to the dynamic modulus after 28 days drying for the Series O concretes. These calculated values are presented in table 13–12. It may be noted that an increase in C_3S and probably Na_2O was associated with an increase in dynamic modulus. Increases in air content, SO_3 and probably C_4AF and fineness were associated with a decrease in dynamic modulus. Of these independent variables, differences in air content, C_3S, and SO_3 showed the greatest calculated ranges of contribution to OD42.

6.2.2. Dynamic Modulus of Series A Concretes

The frequency distribution of the dynamic modulus after 28 days drying of the Series A concretes is presented in table 13–13. There was a broad distribution of values and an overlapping of the values obtained with the different types of cement. The concrete specimens were moist cured 14 days and then dried in laboratory air for 28 days.

Selected equations are presented in table 13–14 to indicate the independent variables associated with the dynamic modulus values. Equation 1 indicates the effect of air content, eq 2 the effect of the w/c, and eq 3 the effect of both of these vari-

TABLE 13–6. *Coefficients for equations relating AD14, the dynamic Young's modulus NAE cements, to various*

Eq. No.	Note	10^6 psi	Const.	Air content	w/c	C_3S	C_4AF	CaO
1	1	AD14 s.d.	= +4.893 = (0.027)	−0.0648 (0.0092)	---------- ----------	---------- ----------	---------- ----------	---------- ----------
2	1	AD14 s.d.	= +2.498 = (0.551)	---------- ----------	+3.551 (0.864)	---------- ----------	---------- ----------	---------- ----------
3	1	AD14 s.d.	= +5.928 = (0.798)	−0.0786 (0.0141)	−1.580 (1.218)	---------- ----------	---------- ----------	---------- ----------
4	1	AD14 s.d.	= +8.044 = (0.615)	−0.1451 (0.0111)	−6.703 (0.931)	+0.0189 (0.0021)	−0.0291 (0.0064)	---------- ----------
5	1	AD14 s.d.	= +7.870 = (0.611)	−0.1406 (0.0111)	−6.435 (0.927)	+0.0190 (0.0021)	−0.0273 (0.0064)	---------- ----------
5A	2	AD14 (odd) s.d.	= +9.259 = (0.962)	−0.1600 (0.0157)	−8.114 (1.486)	+0.0190 (0.0029)	−0.0453 (0.0096)	---------- ----------
5B	3	AD14 (even) s.d.	= +6.838 = (0.781)	−0.1248 (0.0162)	−5.275 (1.147)	+0.0212 (0.0030)	−0.0109 (0.0084)	---------- ----------
6	1	AD14 s.d.	= +9.244 = (1.336)	−0.1466 (0.0116)	−6.932 (1.007)	---------- ----------	---------- ----------	+0.0654 (0.0136)
7	1	AD14 s.d.	= +7.445 = (2.530)	−0.1427 (0.0116)	−6.689 (0.999)	---------- ----------	---------- ----------	+0.0830 (0.0268)
7A	2	AD14 (odd) s.d.	= +13.057 = (4.015)	−0.1654 (0.0164)	−8.823 (1.600)	---------- ----------	---------- ----------	*+0.0403 (0.0416)
7B	3	AD14 (even) s.d.	= +7.744 = (3.583)	−0.1259 (0.0170)	−5.350 (1.234)	---------- ----------	---------- ----------	+0.0776 (0.0378)

Note 1, 173 cements, Avg. = 4.762 × 10^6 psi, S.D. = 0.2860 × 10^6 psi. *Coef./s.d. ratio less than 1.
Note 2, 87 cements
Nore 3, 86 cements

TABLE 13–7. *Coefficients for equations relating AD14, the dynamic Young's modulus cements, to various*

Eq. No.	Note	10^6 psi	Const.	Air content	w/c	C_3S	C_4AF	CaO	SiO_2
1	1	AD14 s.d.	= +4.786 = (0.0392)	*+0.0087 (0.0221)	---------- ----------	---------- ----------	---------- ----------	---------- ----------	---------- ----------
2	1	AD14 s.d.	= +5.218 = (0.657)	---------- ----------	*−0.654 (1.024)	---------- ----------	---------- ----------	---------- ----------	---------- ----------
3	1	AD14 s.d.	= +5.196 = (0.817)	*+0.0012 (0.0266)	*−0.622 (1.236)	---------- ----------	---------- ----------	---------- ----------	---------- ----------
4	1	AD14 s.d.	= +7.930 = (0.659)	−0.1196 (0.0213)	−6.619 (0.999)	+0.0189 (0.0022)	−0.0280 (0.0066)	---------- ----------	---------- ----------
5	1	AD14 s.d.	= +7.784 = (0 652)	−0.1149 (0.0215)	−6.345 (0.990)	+0.0186 (0.0022)	−0.0240 (0.0069)	---------- ----------	---------- ----------
5A	2	AD14 (odd) s.d.	= +8.409 = (0.964)	−0.0889 (0.0332)	−6.821 (1.449)	+0.0160 (0.0031)	−0.0358 (0.0105)	---------- ----------	---------- ----------
5B	2	AD14 (even) s.d.	= +7.375 = (0.828)	−0.1492 (0.0260)	−6.169 (1.278)	+0.0229 (0.0030)	−0.0134 (0.0087)	---------- ----------	---------- ----------
6	1	AD14 s.d.	= +9.385 = (1.375)	−0.1222 (0.0216)	−6.987 (1.077)	---------- ----------	---------- ----------	+0.0638 (0.0140)	−0.155 (0.022)
7	1	AD14 s.d.	= +9.991 = (1.396)	−0.1173 (0.0217)	−6.750 (1.604)	---------- ----------	---------- ----------	+0.0545 (0.0145)	−p.159 (0.022)
7A	2	AD14 (odd) s.d.	= +8.560 = (2.003)	−0.0877 (0.0331)	−7.243 (1.516)	---------- ----------	---------- ----------	+0.0667 (0.0214)	−0.126 (0.032)
7B	2	AD14 (even) s.d.	= +13.090 = (2.030)	−0.1416 (0.0273)	−6.034 (1.419)	---------- ----------	---------- ----------	+0.0318 (0.0195)	−0.226 (0.033)

Note 1, 162 cements, S.D. = 0.2466 x 10^6 psi
Note 2, 81 cements
*Coef./s.d. ratio less than one.

of elasticity in 10^6 psi after 14 days moist curing of Series A concretes made of AE + independent variables

SiO_2	Al_2O_3	Fe_2O_3	SO_3	Na_2O	K_2O	MgO	Rb	Mn	S.D.
------	------	------	------	------	------	------	------	------	0.2529
------	------	------	------	------	------	------	------	------	0.2736
------	------	------	------	------	------	------	------	------	0.2524
------	------	------	+0.208 (0.043)	+0.290 (0.080)	+0.303 (0.066)	+0.0159 (0.0121)	------	------	0.1698
------	------	------	+0.211 (0.042)	+0.270 (0.079)	+0.222 (0.073)	+0.0226 (0.0123)	+14.86 (7.68)	−0.185 (0.111)	0.1675
------	------	------	+0.114 (0.066)	* +0.061 (0.131)	+0.455 (0.111)	+0.0244 (0.0177)	* +5.86 (11.93)	* −0.116 (0.139)	0.1722
------	------	------	+0.255 (0.054)	+0.271 (0.100)	* −0.001 (0.099)	+0.0320 (0.0166)	+21.34 (9.65)	−0.282 (0.197)	0.1518
−0.153 (0.022)	−0.126 (0.025)	−0.126 (0.021)	+0.134 (0.049)	+0.273 (0.081)	+0.289 (0.074)	------	------	------	0.1706
−0.139 (0.028)	−0.111 (0.032)	−0.105 (0.030)	+0.161 (0.058)	+0.266 (0.083)	+0.210 (0.081)	+0.0277 (0.0249)	+14.16 (7.78)	−0.193 (0.114)	0.1683
−0.173 (0.042)	−0.125 (0.048)	−0.201 (0.049)	* −0.011 (0.097)	* −0.018 (0.144)	+0.394 (0.121)	* −0.0054 (0.0396)	* +1.42 (12.48)	−0.152 (0.143)	0.1721
−0.170 (0.041)	−0.148 (0.044)	−0.070 (0.038)	+0.181 (0.073)	+0.262 (0.107)	* −0.018 (0.117)	* +0.0252 (0.0327)	+21.71 (9.86)	−0.307 (0.218)	0.1538

of elasticity in 10^6 psi after 14 days moist curing of Series A concretes made of NAE independent variables

Al_2O_3	Fe_2O_3	SO_3	Na_2O	K_2O	MgO	Rb	Mn	Cu	S.D.
------	------	------	------	------	------	------	------	------	0.2472
------	------	------	------	------	------	------	------	------	0.2470
------	------	------	------	------	------	------	------	------	0.2478
------	------	+0.225 (0.045)	+0.269 (0.082)	+0.273 (0.069)	+0.0151 (0.0124)	------	------	------	0.1701
------	------	+0.227 (0.044)	+0.248 (0.082)	+0.173 (0.078)	+0.0207 (0.0126)	+12.59 (7.83)	−0.239 (0.118)	−2.11 (1.66)	0.1674
------	------	+0.260 (0.065)	* +0.107 (0.134)	+0.124 (0.121)	* +0.0059 (0.0185)	* +6.67 (11.33)	−0.380 (0.157)	−6.56 (2.54)	0.1762
------	------	+0.187 (0.057)	+0.316 (0.095)	* +0.037 (0.100)	+0.0652 (0.0172)	+29.53 (10.32)	* −0.067 (0.167)	* +0.64 (2.02)	0.1422
−0.123 (0.026)	−0.125 (0.022)	+0.148 (0.050)	+0.248 (0.084)	+0.245 (0.078)	------	------	------	------	0.1704
−0.125 (0.026)	−0.118 (0.022)	+0.140 (0.050)	+0.218 (0.084)	+0.135 (0.086)	------	+11.41 (7.90)	−0.267 (0.121)	−2.14 (1.66)	0.1676
−0.083 (0.035)	−0.127 (0.035)	+0.201 (0.077)	* +0.089 (0.138)	* +0.085 (0.130)	------	* +3.93 (11.62)	−0.420 (0.160)	−6.30 (2.55)	0.1762
−0.207 (0.039)	−0.120 (0.028)	* +0.034 (0.069)	+0.272 (0.101)	* +0.019 (0.115)	------	+27.55 (10.64)	* −0.161 (0.184)	* −0.01 (2.09)	0.1465

TABLE 13-8. *Calculated contributions of independent variables to AD14, the 14-day dynamic modulus of Series A concretes*

Independent variable	Range of variables (percent)	Coefficients from eq 5 table 13-7	Calculated contributions to AD14	Calculated range of contributions to AD14
Air-content, NAE cements	0 to 4.5	−0.1149	Const. = +7.78 0 to −0.52	0.52
w/c	0.6 to 0.7	−6.345	−3.81 to −4.44	0.63
C_3S	20 to 65	+0.0186	+0.37 to +1.20	0.83
C_4AF	1 to 16	−0.0240	−0.02 to −0.38	0.36
SO_3	1.2 to 3.0	+0.227	+0.27 to +0.68	0.41
Na_2O	0 to 0.7	+0.248	0 to +0.17	0.17
K_2O	0 to 1.1	+0.173	0 to +0.19	0.19
MgO*	0 to 5	+0.0207	0 to +0.10	0.10
Rb*	0 to 0.01	+12.59	0 to +0.13	0.13
Mn	0 to 1.0	−0.239	0 to −0.24	0.24
Cu*	0 to 0.05	−0.211	0 to −0.01	0.01

*Coefficient of doubtful significance as coef./s.d. ratio was less than 2.

ables. The sign of the coefficient for w/c was positive in eq 2 and negative in eq 3 and not highly significant. In eq 4, where other commonly determined variables were included, the coefficients for both air content and w/c were negative and highly significant. The use of the independent variables in eqs 1, 2, or 3 resulted in a significant reduction in the S.D. value. (See table 13-57.) With the additional use of the trace elements Cu, Li, and Zr in eq 4, the reduction in variance was significant at the 5.0-percent level.

Equations 5A and 5B calculated for the "odds" and "evens" in the array of cements indicated that C_3A, C_4AF, fineness, Loss, Cu, Li, and Zr had coef./s.d. valyes less than 1.0 in one or both of the equations calculated for the smaller groups of cement.

The use of SiO_2, Al_2O_3, and Fe_2O_3 in eq 6 instead of the potential compounds but with other commonly determined variables resulted in an S.D. value similar to that of eq 4. The variables Loss and Zr had coef./s.d. ratios less than 1.0 in eq 6. The use of the trace elements Cu and Li in addition to the commonly determined variables resulted in a reduction in variance significant at the 5.0-percent level. (See table 13-57.)

Equations calculated for the dynamic modulus after 28 days drying of the Series A concretes made with the NAE cements are presented in table 13-15. In eqs 1, 2, and 3 the air content and w/c were not significant when used as independent variables. However, in eqs 4 through 7, where other commonly determined variables were included, the coefficients were highly significant for both air content and w/c. The use of the commonly determined variables in eq 4 resulted in a highly significant reduction in variance, but with the added trace elements Cu, Li, and Zr in eq 6 the reduction in variance was significant at the 5.0-percent level. (See table 13-57.)

Calculations made for the "odds" and "evens" in the array of cements are presented in eqs 5A and 5B. There were instances where the independent variables MgO, fineness, Loss, Cu, Li, and Zr had coef./s.d. ratios of less than 1.0 in one or the other of the equations for the smaller groups of cement.

With the use of SiO_2, Al_2O_3, and Fe_2O_3 instead of the potential compounds but with the other commonly determined variables, there was a highly significant reduction in variance. The independent variables, Loss and Zr, had coef./s.d. ratios less than 1.0. The use of Cu and Li together with commonly determined variables in eq 7 resulted in a reduction in variance significant at the 5.0-percent level.

Equations calculated for the "odds" and "evens" in the array of cements indicated that MgO, Cu, and Li had coef./s.d. values of less than 1.0 in one or the other of the smaller groups of cement.

Using the independent variables of eq 5, table 13-15, and the ranges of these variables, calculations were made of the estimated contributions to the dynamic-modulus values. These calculated values together with the calculated ranges of values are presented in table 13-16. Increase in C_3S, SO_3 and possibly MgO was associated with higher dynamic-modulus values. Increases in air content, w/c and possibly C_4AF, fineness, and Cu were associated with decreases in the dynamic-modulus values. Differences in air content, w/c, C_3S, and SO_3 showed the greatest calculated range of contributions to AD42.

TABLE 13-9. *Frequency distribution of cements with respect to OD42, the dynamic modulus of elasticity of Series O concretes at 42 days after 14 days moist curing and the storage in air for 28 days*

Type cement	Dynamic modulus of elasticity, 10^6 psi											
	3.2 to 3.4	3.4 to 3.6	3.6 to 3.8	3.8 to 4.0	4.0 to 4.2	4.2 to 4.4	4.4 to 4.6	4.6 to 4.8	4.8 to 5.0	5.0 to 5.2	5.2 to 5.4	Total
	Number of cements											
I					2	7	13	33	20	6	1	82
IA	2	1	2	2	1							8
II		1		1	5	12	18	14	13	4		68
IIA		1			1		1					3
III							1	6	5	5	3	20
IIIA					2			1				3
IV, V		1	1		2	3	6		2			15
Total	2	4	3	3	13	22	39	54	40	15	4	199

TABLE 13–10. *Coefficients for equations relating OD42, the dynamic Young's modulus of elasticity in 10^6 psi after 14 days moist curing then 28 days drying in laboratory air of Series O concretes made of AE + NAE cements, to various independent variables*

Eq. No.	Note	10^6 psi	Const.	Air content	C_3A	C_3S	C_4AF	SiO_2	Al_2O_3	Fe_2O_3	SO_3	Na_2O	APF	MgO	Cu	S.D.
1	1	OD42	= +3.634	−0.1551	−0.0074	+0.0171	−0.0251				+0.515	+0.194	−0.000103	+0.0287		0.1789
		s.d.	= (0.181)	(0.0079)	(0.0058)	(0.0023)	(0.0076)				(0.049)	(0.084)	(0.000033)	(0.0120)		
2	1	OD42	= +3.665	−0.1549	−0.0086	+0.0168	−0.0224				+0.507	+0.210	−0.000099	+0.0246	−3.284	0.1774
		s.d.	= (0.180)	(0.0078)	(0.0058)	(0.0023)	(0.0076)				(0.049)	(0.083)	(0.000033)	(0.0121)	(1.662)	
2A	2	OD42 (odd)	= +3.942	−0.1447	−0.0109	+0.0149	−0.0208				+0.470	+0.148	−0.000126	+0.0204	−5.310	0.1749
		s.d.	= (0.237)	(0.0099)	(0.0086)	(0.0030)	(0.0109)				(0.073)	(0.111)	(0.000043)	(0.0166)	(2.490)	
2B	3	OD42 (even)	= +3.292	−0.1715	* −0.0044	+0.0196	−0.0253				+0.499	+0.287	* −0.000036	+0.0348	* −1.122	0.1793
		s.d.	= (0.287)	(0.0125)	(0.0078)	(0.0038)	(0.0113)				(0.069)	(0.131)	(0.000053)	(0.0180)	(2.274)	
3	1	OD42	= +10.51	−0.1564				−0.1969	−0.2073	−0.1538	+0.371	+0.149	−0.000120	−0.0363		0.1763
		s.d.	= (0.80)	(0.0077)				(0.0254)	(0.0293)	(0.0194)	(0.051)	(0.892)	(0.000033)	(0.0129)		
4	1	OD42	= +10.42	−0.1562				−0.1933	−0.2068	−0.1429	+0.366	+0.164	−0.000116	−0.0390	−3.022	0.1751
		s.d.	= (0.80)	(0.0077)				(0.0253)	(0.0290)	(0.0202)	(0.051)	(0.082)	(0.000033)	(0.0129)	(1.642)	
4A	2	OD42 (odd)	= +10.04	−0.1454				−0.1738	−0.1926	−0.1307	+0.324	* +0.107	−0.000136	−0.0373	−5.104	0.1728
		s.d.	= (1.09)	(0.0098)				(0.0334)	(0.0411)	(0.0304)	(0.074)	(0.109)	(0.000043)	(0.0183)	(2.463)	
4B	3	OD42 (even)	= +10.98	−0.1736				−0.2197	−0.2228	−0.1630	+0.366	+0.225	−0.000071	−0.0370	* −0.909	0.1772
		s.d.	= (1.24)	(0.0123)				(0.0401)	(0.0428)	(0.0279)	(0.072)	(0.129)	(0.000054)	(0.0186)	(2.249)	

*Coef./s.d. ratio less than one.

Note 1, 179 cements, Avg. = 4.567 × 10^6 psi, S.D. = 0.3584 × 10^6 psi
Note 2, 90 cements
Note 3, 89 cements

TABLE 13–11. *Coefficients for equations relating OD42, the dynamic Young's modulus of elasticity in 10^6 psi after 14 days moist curing, then 28 days drying in laboratory air of Series O concretes made of NAE cements, to various independent variables*

Eq. No.	Note	10^6 psi	Const.	Air content	C_3A	C_3S	C_4AF	SiO_2	Al_2O_3	Fe_2O_3	SO_3	Na_2O	APF	MgO	Cu	S.D.
1	1	OD42	= +3.59	−0.1597	−0.0086	+0.0181	−0.0235				+0.543	+0.204	−0.000119	+0.0269		0.1761
		s.d.	= (0.19)	(0.0192)	(0.0058)	(0.0024)	(0.0076)				(0.049)	(0.085)	(0.000033)	(0.0120)		
2	1	OD42	= +3.61	−0.1525	−0.0100	+0.0178	−0.0206				+0.534	+0.214	−0.000115	+0.0228	−3.195	0.1747
		s.d.	= (0.19)	(0.0194)	(0.0058)	(0.0024)	(0.0077)				(0.049)	(0.084)	(0.000033)	(0.0121)	(1.677)	
2A	2	OD42 (odd)	= +3.97	−0.1546	−0.0116	+0.0151	−0.0290				+0.553	* +0.120	−0.000145	* +0.0045	* −2.314	0.1848
		s.d.	= (0.26)	(0.0291)	(0.0092)	(0.0032)	(0.0114)				(0.083)	(0.121)	(0.000047)	(0.0192)	(2.578)	
2B	3	OD42 (even)	= +2.94	−0.1570	* −0.0037	+0.0247	* −0.0072				+0.521	+0.359	−0.000090	+0.0441	* −1.545	0.1659
		s.d.	= (0.30)	(0.0236)	(0.0079)	(0.0039)	(0.0115)				(0.065)	(0.131)	(0.000051)	(0.0169)	(2.470)	
3	1	OD42	= +10.75	−0.1609				−0.2046	−0.2171	−0.1513	+0.393	+0.158	−0.000133	−0.0411		0.1743
		s.d.	= (0.81)	(0.0189)				(0.0258)	(0.0296)	(0.0195)	(0.051)	(0.083)	(0.000034)	(0.0130)		
4	1	OD42	= +10.64	−0.1542				−0.2008	−0.2167	−0.1395	+0.387	+0.168	−0.000129	−0.0436	−2.945	0.1731
		s.d.	= (0.81)	(0.0192)				(0.0257)	(0.0295)	(0.0205)	(0.051)	(0.083)	(0.000034)	(0.0130)	(1.663)	
4A	2	OD42 (odd)	= +10.19	−0.1562				−0.1790	−0.2005	−0.1514	+0.397	* +0.101	−0.000151	−0.0478	* −2.380	0.1816
		s.d.	= (1.12)	(0.0286)				(0.0349)	(0.0435)	(0.0306)	(0.083)	(0.119)	(0.000046)	(0.0205)	(2.533)	
4B	3	OD42 (even)	= +11.84	−0.1576				−0.2500	−0.2482	−0.1353	+0.360	+0.269	−0.000117	−0.0462	* −1.281	0.1699
		s.d.	= (1.29)	(0.0270)				(0.0420)	(0.0431)	(0.0297)	(0.070)	(0.131)	(0.000054)	(0.0183)	(2.547)	

*Coef./s.d. ratio less than one.

Note 1, 167 cements, Avg. = 4.624 × 10^6 psi, S.D. = 0.2882 × 10^6 psi
Note 2, 84 cements
Note 3, 83 cements

TABLE 13–12. *Calculated contributions of independent variables to OD42, the dynamic modulus after 14 days moist curing followed by 28 days in laboratory air of Series O concretes.*

Independent variable	Range of variables (percent)	Coefficients from eq 2 table 13–11	Calculated contributions to OD42	Calculated range of contributions to OD42
			Const. = +3.61	
Air-content, NAE cements	0 to 4.5	−0.1525	0 to −0.69	0.69
C_3A**	1 to 15	−0.010	−0.01 to −0.15	0.14
C_3S	20 to 65	+0.0178	+0.35 to +1.16	0.81
C_4AF	1 to 16	−0.0206	−0.02 to −0.32	0.30
SO_3	1.2 to 3.0	−0.534	−0.64 to −1.60	0.96
Na_2O	0 to 0.7	+0.214	0 to +0.15	0.15
APF	*2500 to 5500	−0.000115	−0.29 to −0.63	0.34
MgO**	0 to 5.0	+0.0228	0 to +0.11	0.11
Cu**	0 to 0.05	−3.195	0 to −0.16	0.16

*cm^2/g.
**Coefficient of doubtful significance as the coef./s.d. ratio was less than 2

6.3. Dynamic Modulus After 56 Days Drying

6.3.1. Dynamic Modulus of Series O Concretes

The frequency distribution of the dynamic modulus of Series O concretes after 56 days drying is presented in table 13–17. The concrete specimens had been moist-cured for 14 days then dried in laboratory air for 8 weeks. There was a broad distribution of values and an overlapping of values obtained with the different types of cements.

Equations are presented in table 13–18 indicating the variables associated with the dynamic modulus of the air-dried Series O concretes made with AE + NAE cements. Commonly determined variables having a coef./s.d. ratio greater than 1.0 when used in the multivariable equation (eq 1) resulted in a highly significant reduction in variance. (See table 13–57.) The only trace element

TABLE 13–13. *Frequency distribution of cements with respect to AD42, the dynamic modulus of elasticity of Series A concretes at 42 days (moist curing 14 days and then drying in laboratory air for 28 days)*

Type cement	Dynamic modulus of elasticity, 10^6 psi											
	3.4 to 3.6	3.6 to 3.8	3.8 to 4.0	4.0 to 4.2	4.2 to 4.4	4.4 to 4.6	4.6 to 4.8	4.8 to 5.0	5.0 to 5.2	5.2 to 5.4	5.4 to 5.6	Total
	Number of cements											
I			1	1	9	23	29	12	1	3		79
IA	1		1	2	1	3						8
II			2	6	13	13	16	12	5			67
IIA	1					2						3
III						2	6	5	6		1	20
IIIA						1	2					3
IV, V		2		2	5	2	2	2				15
Total	2	2	4	11	28	46	55	31	12	3	1	195

TABLE 13–14. *Coefficients for equations relating AD42, the dynamic Young's modulus ratory air of Series A concretes made of AE +*

Eq. No.	Note	10^6 psi	Const.	Air content	w/c	C_3A	C_3S	C_4AF	SiO_2
1	1	AD42	= +4.675	−0.0499					
		s.d.	= (0.030)	(0.0103)					
2	1	AD42	= +2.911		+2.609				
		s.d.	= (0.592)		(0.928)				
3	1	AD42	= +5.644	−0.0631	−1.511				
		s.d.	= (0.892)	(0.0158)	(1.360)				
4	1	AD42	= +7.961	−0.1281	−6.879	−0.0118	+0.0174	−0.0247	
		s.d.	= (0.721)	(0.0132)	(1.134)	(0.0067)	(0.0026)	(0.0084)	
5	1	AD42	= +7.766	−0.1260	−6.649	−0.0102	+0.0173	−0.0193	
		s.d.	= (0.715)	(0.0130)	(1.121)	(0.0068)	(0.0026)	(0.0085)	
5A	2	AD42 (odd)	= +9.511	−0.1480	−8.753	*−0.0088	+0.0149	−0.0340	
		s.d.	= (1.166)	(0.0190)	(1.868)	(0.0104)	(0.0037)	(0.0127)	
5B	3	AD42 (even)	= +5.855	−0.0993	−4.415	−0.0113	+0.0211	*−0.0075	
		s.d.	= (0.957)	(0.0198)	(1.456)	(0.0098)	(0.0037)	(0.0130)	
6	1	AD42	= +15.23	−0.1289	−6.780				−0.212
		s.d.	= (1.15)	(0.0129)	(1.114)				(0.028)
7	1	AD42	= +14.89	−0.1264	−6.523				−0.207
		s.d.	= (1.14)	(0.0128)	(1.102)				(0.028)
7A	2	AD42 (odd)	= +16.29	−0.1498	−8.768				−0.197
		s.d.	= (1.69)	(0.0185)	(1.821)				(0.040)
7B	3	AD42 (even)	= +13.89	−0.1009	−4.212				−0.232
		s.d.	= (1.61)	(0.0196)	(1.432)				(0.041)

Note 1, 173 cements, Avg. = 4.574 × 10^6 psi, S.D. = 0.2999 × 10^6 psi
Note 2, 87 cements
Note 3, 86 cements
*Coef./s.d. ratio less than 1.

having a coef./s.d. ratio greater than 1.0 when used with other commonly determined variables was vanadium. The additional use of V in eq 2 did not result in a significant reduction in variance. Equations 2A and 2B calculated for the "odds" and "evens" in the array of cements indicated that K_2O as well as V had coef./s.d. ratios less than 1.0 in one or both of the smaller groups of cement.

Equations 3 and 4, calculated using the major oxides instead of the potential compounds, resulted in approximately the same S.D. values. The coef./s.d. ratio for K_2O was less than 1.0, and that for Loss in eq 4B was less than 1.0. The average value for the dynamic modulus after 8 weeks drying was 4.43×10^6 psi, after 4 weeks drying it was 4.57×10^6 psi, and after 14 days moist curing before the drying cycle, the average value was 4.75×10^6 psi. (See tables 13–18, 13–10, and 13–2.)

A similar set of equations for the Series O concretes made with NAE cements is presented in table 13–19. The use of the commonly determined variables, air content, C_3A, C_3S, C_4AF, SO_3, K_2O, fineness, Loss, and MgO in eq 1 resulted in a highly significant reduction in variance. The use of V in eqs 2 or 4 in addition to other commonly determined variables did not result in a reduction in variance significant at the 0.05 probability level. The coefficient for the air content of the NAE cements was highly significant, but the coef./s.d. ratio was somewhat smaller than when the AE cements were included as in the previous table.

Using the coefficients of the independent variables of eq 2 of table 13–19 as well as their ranges of values, calculations were made of their estimated contribution to the dynamic modulus after 56 days drying and the calculated ranges of these contributions. These calculated values are presented in table 13–20. Increases of C_3S, SO_3 and possibly loss on ignition and MgO were associated with increases in dynamic modulus values. Higher values for air content, C_3A, C_4AF, and fineness were associated with lower values for dynamic modulus.

6.3.2. Dynamic Modulus of Series A Concretes

The frequency distribution of the dynamic modulus of the air-dried Series A concretes is presented in table 13–21. The use of a 5 ± 1-in slump rather than a constant water/cement ratio resulted in slightly higher values for the AE cements (types IA, IIA, and IIIA) than was observed in table 13–17. There was a broad distribution of values and an overlapping of the values obtained with the different types of cement.

Equations are presented in table 13–22 indicating the variables associated with the dynamic modulus of the Series A concretes made of AE + NAE cements. Equations 1, 2, 3, and 4 show that using the air content and the water/cement ratio, singly or together, and with other commonly determined variables, resulted in differences in the values for the coefficients as well as in their coef./s.d. ratios. Whereas the coefficient for w/c was positive in eq 2, it was negative in eqs 4 through 7. As indicated in table 13–57, the reduction in vari-

of elasticity in 10^6 psi after 14 days moist curing followed by 28 days drying in labo-
NAE cements, to various independent variables

Al_2O_3	Fe_2O_3	SO_3	MgO	APF	Loss	Cu	Li	Zr	S.D.
----------	----------	----------	----------	----------	----------	----------	----------	----------	0.2821
----------	----------	----------	----------	----------	----------	----------	----------	----------	0.2940
----------	----------	----------	----------	----------	----------	----------	----------	----------	0.2819
----------	----------	+0.517 (0.056)	+0.0421 (0.0133)	−0.000120 (0.000038)	+0.0629 (0.0314)	----------	----------	----------	0.1944
----------	----------	+0.508 (0.056)	+0.0348 (0.0138)	−0.000104 (0.000038)	+0.0452 (0.0319)	−4.41 (1.89)	+9.11 (4.64)	+0.381 (0.372)	0.1914
----------	----------	+0.503 (0.086)	+0.0350 (0.0203)	−0.000145 (0.000054)	+0.0751 (0.0491)	−5.33 (2.83)	* +6.92 (7.53)	* +0.313 (0.424)	0.1984
----------	----------	+0.439 (0.081)	+0.0429 (0.0197)	* −0.000020 (0.000062)	* −0.0180 (0.0465)	* −2.95 (2.99)	* +6.33 (6.78)	* +0.115 (0.982)	0.1834
−0.234 (0.033)	−0.152 (0.022)	+0.379 (0.057)	−0.0277 (0.0143)	−0.000119 (0.000037)	----------	----------	----------	----------	0.1913
−0.227 (0.033)	−0.136 (0.023)	+0.365 (0.056)	−0.0352 (0.0144)	−0.000109 (0.000036)	----------	−4.33 (1.86)	+8.34 (4.50)	----------	0.1885
−0.215 (0.048)	−0.173 (0.035)	+0.388 (0.082)	−0.0334 (0.0202)	−0.000148 (0.000051)	----------	−5.81 (2.73)	* +7.05 (7.12)	----------	0.1935
−0.257 (0.047)	−0.111 (0.032)	+0.283 (0.082)	−0.0322 (0.0203)	* −0.000037 (0.000057)	----------	* −2.85 (2.96)	* +5.85 (6.65)	----------	0.1817

TABLE 13–15. *Coefficients for equations relating AD42, the dynamic Young's modulus of ratory air of Series A concretes made of NAE*

Eq. No.	Note	10^6 psi	Const.	Air content	w/c	C_3A	C_3S	C_4AF	SiO_2
1	1	AD42	= +4.621	*−0.0153					
		s.d.	= (0.044)	(0.0249)					
2	1	AD42	= +4.742		*−0.226				
		s.d.	= (0.741)		(1.155)				
3	1	AD42	= +5.212	*−0.0260	*−0.895				
		s.d.	= (0.919)	(0.0300)	(1.391)				
4	1	AD42	= +7.983	−0.1270	−6.905	−0.0127	+0.0172	−0.0263	
		s.d.	= (0.766)	(0.0239)	(1.202)	(0.0068)	(0.0026)	(0.0084)	
5	1	AD42	= +7.756	−0.1231	−6.645	−0.0111	+0.0170	−0.0206	
		s.d.	= (0.756)	(0.0240)	(1.186)	(0.0069)	(0.0026)	(0.0085)	
5A	2	AD42 (odd)	= +8.503	−0.1195	−7.462	−0.0164	+0.0152	−0.0408	
		s.d.	= (1.080)	(0.0371)	(1.703)	(0.0116)	(0.0038)	(0.0145)	
5B	2	AD42 (even)	= +6.899	−0.1378	−5.382	−0.0144	+0.0183	−0.0129	
		s.d.	= (1.084)	(0.0330)	(1.688)	(0.0089)	(0.0039)	(0.0110)	
6	1	AD42	= +15.07	−0.1323	−6.898				−0.205
		s.d.	= (1.19)	(0.0235)	(1.186)				(0.029)
7	1	AD42	= +14.71	−0.1286	−6.624				−0.199
		s.d.	= (1.18)	(0.0236)	(1.173)				(0.028)
7A	2	AD42 (odd)	= +15.17	−0.1263	−7.542				−0.190
		s.d.	= (1.63)	(0.0359)	(1.662)				(0.040)
7B	2	AD42 (even)	= +14.33	−0.0388	−5.286				−0.214
		s.d.	= (1.79)	(0.0323)	(1.660)				(0.044)

Note 1, 162 cements, Avg. = 4.598 × 10^6 psi, S.D. = 0.2777 × 10^6 psi
Note 2, 81 cements
*Coef./s.d. ratio less than one.

TABLE 13–16. *Calculated contributions of independent variables to AD42, the dynamic modulus after 14 days moist curing followed by 28 days in laboratory air of Series A concretes*

Independent variable	Range of variables (percent)	Coefficients from eq 5 table 13–15	Calculated contributions to AD42	Calculated range of contributions to AD42
			Const. = +7.756	
Air-content, NAE cements	0 to 4.5	−0.1231	0 to −0.55	0.55
w/c	0.6 to 0.7	−6.645	−3.99 to −4.65	0.66
C_3A**	1 to 15	−0.0111	−0.01 to −0.16	0.15
C_3S	20 to 65	+0.0170	+0.34 to +1.11	0.77
C_4AF	1 to 17	−0.0206	−0.02 to −0.35	0.33
SO_3	1.2 to 3.0	+0.513	+0.62 to +1.54	0.92
MgO	0 to 5.0	+0.0344	0 to +0.17	0.17
APF	*2500 to 5500	−0.000093	−0.23 to −0.51	0.28
Loss**	0.3 to 3.3	+0.0340	+0.01 to +0.11	0.10
Cu	0 to 0.05	−4.41	0 to −0.22	0.22
Li**	0 to 0.02	+9.20	0 to +0.18	0.18
Zr**	0 to 0.5	+0.468	0 to +0.23	0.23

*cm^2/g.
**Coefficient of doubtful significance as coef./s.d. ration was less than 2.

ance was highly significant for each of the first four equations. The use of Li (the only trace element with a coef./s.d. ratio greater than 1.0) in eqs 5 and 7 together with the commonly determined variables did not result in a significant reduction in variance.

In equations calculated for the "odds" and "evens," eqs 5A, 5B, 7A, and 7B, there were instances where the coef./s.d. ratios of K_2O, fineness, and Li were less than 1.0 in one or both of the equations for the smaller groups of cements. The coef./s.d. ratio for Loss was less than 1.0 when included in equations calculated using the oxides (eqs 6 and 7) rather than the potential compounds as in eqs 4 and 5.

A similar series of equations is presented in table 13–23 for the NAE cements. Equations 2 and 3 of this table do not indicate a relationship to the water/cement ratio. However, when w/c was included with other commonly determined variables as in eqs 4 and 6, its coefficient was highly significant. The relationship of various independent variables to the water requirements of pastes, mortars, and concrete was discussed in part 1, section 2 of this series of articles [16]. The use of the commonly determined variables, air content, w/c, C_3A, C_3S, C_4AF, SO_3, K_2O, APF, Loss, and MgO in eq 4 resulted in a highly significant reduction of variance. (See table 13–57.) The only trace element that had a coef./s.d. ratio greater than 1.0 when used with the commonly determined variables was Li. The use of Li in eqs 5 and 7 did not result in a reduction of variance significant at the 5.0-percent level.

There were instances in equations calculated for the "odds" and "evens" (eqs 5A, 5B, 7A, and 7B) where the coef./s.d. ratios for fineness, MgO, and Li were less than 1.0 in one or the other of the pairs of equations calculated for the smaller groups of cements.

Using the coefficients of the independent variables of eq 5 of table 13–23 as well as their ranges of values, calculations were made of their estimated contributions to the dynamic modulus after 56 days drying and the calculated ranges of these

elasticity in 10^6 psi after 14 days moist curing followed by 28 days drying in labo-
cements, to various independent variables

Al_2O_3	Fe_2O_3	SO_3	MgO	APF	Loss	Cu	Li	Zr	S.D.
									0.2783
									0.2786
									0.2788
		+0.521 (0.056)	+0.0415 (0.0134)	−0.000110 (0.000039)	+0.0534 (0.0318)				0.1913
		+0.513 (0.056)	+0.0344 (0.0139)	−0.000093 (0.000038)	+0.0340 (0.0322)	−4.41 (1.88)	+9.20 (4.62)	+0.468 (0.367)	0.1877
		+0.526 (0.088)	*+0.0096 (0.0220)	*−0.000061 (0.000066)	+0.0699 (0.0632)	−7.87 (2.86)	*+7.34 (7.78)	*+2.514 (3.030)	0.1984
		+0.490 (0.081)	+0.0635 (0.0188)	−0.000114 (0.000048)	*+0.0275 (0.0394)	*−1.35 (2.79)	+6.93 (6.72)	+0.478 (0.357)	0.1737
−0.229 (0.033)	−0.153 (0.022)	+0.387 (0.057)	−0.0262 (0.0143)	−0.000109 (0.000037)					0.1890
−0.221 (0.033)	−0.137 (0.023)	+0.373 (0.057)	−0.0338 (0.0144)	−0.000100 (0.000037)		−4.27 (1.86)	+8.39 (4.51)		0.1860
−0.222 (0.043)	−0.183 (0.037)	+0.400 (0.087)	−0.0563 (0.0228)	−0.000063 (0.000061)		−8.07 (2.78)	*+6.77 (7.06)		0.1954
−0.247 (0.053)	−0.111 (0.031)	+0.324 (0.083)	*−0.0110 (0.0191)	−0.000120 (0.000046)		*−1.71 (2.74)	+7.91 (6.63)		0.1717

TABLE 13–17. *Frequency distribution of cements with respect to OD70, the dynamic modulus of elasticity of Series O concretes at 70 days (14 days moist curing and then storage in laboratory air for 8 weeks)*

Type cement	Dynamic modulus of elasticity, 10^6 psi											
	3.2 to 3.4	3.4 to 3.6	3.6 to 3.8	3.8 to 4.0	4.0 to 4.2	4.2 to 4.4	4.4 to 4.6	4.6 to 4.8	4.8 to 5.0	5.0 to 5.2	5.2 to 5.4	Total
	Number of cements											
I				2	9	15	31	10	12	3		82
IA	3	1	3	1								8
II	1			6	4	21	15	10	10	1		68
IIA	1			1		1						3
III						1	3	4	4	5	3	20
IIIA				1	1		1					3
IV, V		2		1	2	4	4	1	1			15
Total	5	3	3	12	16	42	54	25	27	9	3	199

contributions. These calculated values are presented in table 33–24. Higher values for air content, w/c, C_3A, and C_4AF were associated with lower values for dynamic modulus. Higher values for C_3S, SO_3, and probably K_2O, Loss, and MgO were associated with higher values for dynamic modulus of the air-dried concrete.

6.4. Dynamic Modulus After 28 Days Resoaking

6.4.1. Dynamic Modulus of Series O Concretes

After 14 days moist-air curing, then 8 weeks drying in laboratory air, the concrete specimens were placed in water and the dynamic modulus was again determined after 28 days of soaking.

The frequency distribution of dynamic modulus after 28 days resoaking of the Series O concretes is presented in table 13–25.

There was a fairly broad distribution of values for the concretes made of NAE cements and an overlapping of the values for the cements of the different types.

A series of equations is presented in table 13–26 to indicate the independent variables found to have coef./s.d. ratios greater than 1.0 and their relation to the values for dynamic modulus after 28 days resoaking. The use of the commonly determined variables, air content, C_3A, C_3S, C_4AF, SO_3, APF, and Loss in eq 1 resulted in a highly significant reduction in variance. (See table 13–57.) The additional use of the trace elements Ba, Cu, and Zr in eq 2 resulted in a further significant reduction in variance. In equations calculated for the "odds" and "evens" in the array of cements (eqs 2A and 2B) there were instances where APF, Loss, Cu, and Zr had coef./s.d. ratios of less than 1.0 in one or the other of the equations for the smaller groups of cements.

TABLE 13–18. *Coefficients for equations relating OD70, the dynamic Young's modulus of elasticity in 10^6 psi after 14 days moist curing, then 56 days drying in laboratory air of Series O concretes made of AE + NAE cements, to various independent variables*

Eq. No.	Note	10^6 psi	Const.	Air content	C_3A	C_3S	C_4AF	SiO_2	Al_2O_3	Fe_2O_3	SO_3	K_2O	APF	Loss	MgO	V	S.D.
1	1	OD70	= +3.449	−0.1569	−0.0234	+0.0183	−0.0290				+0.539	+0.106	−0.000118	+0.120	+0.0339		0.1798
		s.d.	= (0.179)	(0.0079)	(0.0060)	(0.0023)	(0.0077)				(0.052)	(0.076)	(0.000036)	(0.028)	(0.0125)		
2	1	OD70	= +3.523	−0.1567	−0.0256	+0.0181	−0.0302				+0.551	+0.102	−0.000128	+0.116	+0.0308	−1.019	0.1796
		s.d.	= (0.190)	(0.0079)	(0.0063)	(0.0023)	(0.0078)				(0.053)	(0.076)	(0.000037)	(0.028)	(0.0128)	(0.871)	
2A	2	OD70 (odd)	= +3.864	−0.1469	−0.0297	+0.0171	−0.0378				+0.438	+0.268	−0.000140	+0.122	+0.0209	*−1.061	0.1813
		s.d.	= (0.263)	(0.0104)	(0.0094)	(0.0031)	(0.0114)				(0.084)	(0.117)	(0.000052)	(0.043)	(0.0186)	(1.329)	
2B	3	OD70 (even)	= +3.121	−0.1742	−0.0196	+0.0202	−0.0237				+0.589	*−0.042	−0.000074	+0.112	+0.0456	*−0.987	0.1720
		s.d.	= (0.280)	(0.0120)	(0.0082)	(0.0036)	(0.0109)				(0.068)	(0.099)	(0.000055)	(0.040)	(0.0179)	(1.120)	
3	1	OD70	= +10.89	−0.1577				−0.215	−0.260	−0.148	+0.423		−0.000122	+0.0471	−0.0327		0.1807
		s.d.	= (0.87)	(0.0079)				(0.028)	(0.031)	(0.020)	(0.052)		(0.000035)	(0.0303)	(0.0135)		
4	1	OD70	= +10.90	−0.1576				−0.213	−0.264	−0.147	+0.436		−0.000131	+0.0436	−0.0354	−1.044	0.1805
		s.d.	= (0.87)	(0.0078)				(0.028)	(0.031)	(0.020)	(0.053)		(0.000035)	(0.0304)	(0.0137)	(0.875)	
4A	2	OD70 (odd)	= +10.68	−0.1439				−0.196	−0.250	−0.150	+0.375		−0.000171	+0.0641	+0.0334	*−1.325	0.1875
		s.d.	= (1.21)	(0.0105)				(0.039)	(0.046)	(0.032)	(0.082)		(0.000049)	(0.0465)	(0.0205)	(1.371)	
4B	3	OD70 (even)	= +11.41	−0.1784				−0.239	−0.283	−0.152	+0.440		−0.000068	*+0.0281	−0.0334	*−0.804	0.1707
		s.d.	= (1.28)	(0.0118)				(0.042)	(0.044)	(0.027)	(0.071)		(0.000055)	(0.0420)	(0.0183)	(1.110)	

*Coef./s.d. ratio less than one.
Note 1, 179 cements, Avg. = 4.425 × 10^6 psi S.D. = 0.3819 × 10^6 psi
Note 2, 90 cements
Note 3, 89 cements

TABLE 13–19. *Coefficients for equations relating OD70, the dynamic Young's modulus of elasticity in 10^6 psi after 14 days moist curing, then 56 days drying in laboratory air of Series O concretes made of NAE cements, to various independent variables*

Eq. No.	Note	10^6 psi	Const.	Air content	C_3A	C_3S	C_4AF	SiO_2	Al_2O_3	Fe_2O_3	SO_3	K_2O	APF	Loss	MgO	V	S.D.
1	1	OD70	= +3.44	−0.1761	−0.0244	+0.0191	−0.0287				+0.559	+0.132	−0.000125	+0.110	+0.0308		0.1795
		s.d.	= (0.19)	(0.0198)	(0.0061)	(0.0024)	(0.0078)				(0.053)	(0.079)	(0.000037)	(0.029)	(0.0128)		
2	1	OD70	= +3.50	−0.1716	−0.0267	+0.0189	−0.0296				+0.571	+0.124	−0.000135	+0.106	+0.0278	−1.035	0.1793
		s.d.	= (0.20)	(0.0202)	(0.0064)	(0.0024)	(0.0079)				(0.054)	(0.079)	(0.000038)	(0.029)	(0.0131)	(0.893)	
2A	2	OD70 (odd)	= +3.86	−0.1693	−0.0291	+0.0172	−0.0408				+0.527	+0.171	−0.000170	+0.141	*+0.0210	*−0.933	0.1867
		s.d.	= (0.27)	(0.0285)	(0.0097)	(0.0032)	(0.0106)				(0.091)	(0.114)	(0.000052)	(0.044)	(0.0216)	(1.402)	
2B	3	OD70 (even)	= +2.92	−0.1764	−0.0196	+0.0235	−0.0148				+0.559	*+0.063	−0.000066	+0.064	+0.0441	−1.285	0.1724
		s.d.	= (0.31)	(0.0299)	(0.0089)	(0.0039)	(0.0123)				(0.071)	(0.115)	(0.000058)	(0.041)	(0.0175)	(1.220)	
3	1	OD70	= +11.27	−0.1767				−0.226	−0.272	−0.149	+0.442		−0.000133	+0.035	−0.0382		0.1804
		s.d.	= (0.90)	(0.0194)				(0.029)	(0.032)	(0.021)	(0.053)		(0.000035)	(0.031)	(0.0138)		
4	1	OD70	= +11.26	−0.1724				−0.224	−0.276	−0.148	+0.454		−0.000142	+0.032	−0.0410	−1.062	0.1802
		s.d.	= (0.90)	(0.0197)				(0.029)	(0.032)	(0.021)	(0.054)		(0.000036)	(0.031)	(0.0140)	(0.895)	
4A	2	OD70 (odd)	= +10.77	−0.1667				−0.199	−0.257	−0.164	+0.420		−0.000178	+0.078	−0.0315	*−0.060	0.1889
		s.d.	= (1.21)	(0.0284)				(0.038)	(0.047)	(0.029)	(0.089)		(0.000049)	(0.047)	(0.0230)	(1.419)	
4B	3	OD70 (even)	= +12.63	−0.1862				−0.280	−0.314	−0.143	+0.403		−0.000070	*−0.029	−0.0487	−1.152	0.1717
		s.d.	= (1.41)	(0.0284)				(0.046)	(0.047)	(0.031)	(0.073)		(0.000057)	(0.046)	(0.0184)	(1.202)	

*Coef./s.d. ratio less than one.
Note 1, 167 cements, Avg. = 4.481 × 10^6 psi, S.D. = 0.3203 × 10^6 psi
Note 2, 84 cements
Note 3, 83 cements

TABLE 13–20. *Calculated contributions of independent variables to OD70, the dynamic modulus after 14 days moist curing followed by 8 weeks in laboratory air of Series O concretes*

Independent variable	Range of variables (percent)	Coefficients from eq 2 table 13–19	Calculated contributions to OD70	Calculated range of contributions to OD70
			Const. = +3.50	
Air-content, NAE cements	0 to 4.5	−0.1716	0 to −0.77	0.77
C_3A	1 to 15	−0.0267	−0.03 to −0.40	0.37
C_3S	20 to 65	+0.0189	+0.38 to +1.23	0.85
C_4AF	1 to 17	−0.0296	−0.03 to −0.50	0.47
SO_3	1.2 to 3.0	+0.571	+0.69 to +1.71	1.02
K_2O**	0 to 1.1	+0.124	0 to +0.14	0.14
APF	*2500 to 5500	−0.000135	−0.34 to −0.74	0.40
Loss	0.3 to 3.3	+0.106	+0.03 to +0.35	0.32
MgO	0 to 5.0	+0.278	0 to +1.39	1.39
V**	0 to 0.1	−1.035	0 to −0.10	0.10

*cm^2/g.
**Coefficient of doubtful significance as coef./s.d. ratio was less than 2.

Equations 3 and 4 were calculated using the major oxides instead of the potential compounds as in eqs 1 and 2. The S.D. values were about the same in both instances. In eqs 4A and 4B SiO_2 and Fe_2O_3 had coef./s.d. ratios of less than 1.0 in addition to APF, Loss, Cu, and Zr as in eqs 2A and 2B.

A corresponding series of equations for the concretes made with NAE cements is presented in table 13–27. The independent variables, their coefficients, and the coef./s.d. ratios were generally in good agreement with those in table 13–26 where the AE cements were included. In the equations calculated for the "odds" and "evens" (eqs 2A, 2B, 4A, and 4B) Fe_2O_3 and Loss had coef./s.d. ratios of less than 1.0 with the smaller groups of cements in one or the other of the pairs of equations.

Using the independent variables of eq 2, table 13–27, and the ranges of these variables, calculations were made of the estimated contributions to the dynamic modulus at 98 days and the ranges of these contributions. The calculated values are presented in table 13–28. Higher values for air content, C_3A and APF, and possibly C_4AF, Ba, and Cu were associated with lower values for dynamic modulus. Higher values for C_3S, SO_3, Loss, and possibly Zr were associated with higher values for dynamic modulus after 28 days resoaking.

6.4.2. Dynamic Modulus of Series A Concretes

The frequency distribution of the dynamic modulus of the Series A concretes (5 ± 1-in slump) is presented in table 13–29. There was a broad distribution of values and an overlapping of the values obtained with the concretes made of the different types of cement.

A series of equations for concretes made of AE + NAE cements is presented in table 13–30, indicating the independent variables associated with the dynamic modulus of the Series A concretes after the 28-day resoaking period. Equation 1 shows that higher air content and higher w/c were associated with lower dynamic modulus. Other commonly determined variables, C_3A, C_3S, C_4AF, SO_3, and APF were, as indicated in eq 2, also associated with the dynamic modulus after 28 days resoaking. The reduction in variance was highly significant. (See also table 13–57.) The additional use of the trace elements Cu, Zr, Ti, Rb, and Ba together with the commonly determined variables in eq 3 resulted in a further significant reduction in variance.

Equations 3A and 3B calculated for the "odds" and "evens" in the array of cements indicated that the coef./s.d. ratios for fineness, Rb, and Ba were less than 1.0 in one or the other of the equations for the smaller groups of cements.

A corresponding series of equations for the NAE cements is presented in table 13–31. As indicated in eq 1, the dynamic modulus after 28 days resoaking was related to the air content and water/cement ratio of the concrete made of the different cements. The additional use of commonly determined independent variables, C_3A, C_3S, C_4AF, SO_3, and fineness in eq 2 resulted in a significant reduction in variance. (See table 13–57.) Use of

TABLE 13–21. *Frequency distribution of cements with respect to AD70, the dynamic modulus of elasticity of Series A concretes at 70 days (14 days moist curing and then storing in laboratory air for 8 weeks)*

Type cement	Dynamic modulus of elasticity, 10^6 psi											
	3.2 to 3.4	3.4 to 3.6	3.6 to 3.8	3.8 to 4.0	4.0 to 4.2	4.2 to 4.4	4.4 to 4.6	4.6 to 4.8	4.8 to 5.0	5.0 to 5.2	5.2 to 5.4	Total
	Number of cements											
I			1	1	15	13	25	18	5		1	79
IA		1		3	3	1						8
II				4	8	19	12	14	8	2		67
IIA	1					2						3
III						2	2	6	3	6	1	20
IIIA						1		2				3
IV, V		2		1	2	4	4		2			15
Total	1	3	1	9	28	42	43	40	18	8	2	195

TABLE 13–22. *Coefficients for equations relating AD70, the dynamic Young's modulus of elasticity in 10^6 psi after 14 days moist curing followed by 56 days drying in laboratory air of Series A concretes made of AE + NAE cements, to various independent variables*

Eq. No.	Note	10^6 psi	Const.	Air content	w/c	C_3A	C_3S	C_4AF	SiO_2	Al_2O_3	Fe_2O_3	SO_3	K_2O	APF	Loss	MgO	Li	S.D.
1	1	AD70	= +4.551	−0.0584	------	------	------	------	------	------	------	------	------	------	------	------	------	0.2993
		s.d.	= (0.032)	(0.0109)	------	------	------	------	------	------	------	------	------	------	------	------	------	------
2	1	AD70	= +2.329	------	+3.300	------	------	------	------	------	------	------	------	------	------	------	------	0.3132
		s.d.	= (0.631)	------	(0.989)	------	------	------	------	------	------	------	------	------	------	------	------	------
3	1	AD70	= +5.334	−0.0689	*−1.196	------	------	------	------	------	------	------	------	------	------	------	------	0.2996
		s.d.	= (0.947)	(0.0168)	(1.445)	------	------	------	------	------	------	------	------	------	------	------	------	------
4	1	AD70	= +6.783	−0.1247	−5.339	−0.0349	+0.0181	−0.0304	------	------	------	+0.540	+0.215	−0.000097	+0.1016	+0.0391	------	0.1861
		s.d.	= (0.700)	(0.0126)	(1.101)	(0.0068)	(0.0025)	(0.0081)	------	------	------	(0.057)	(0.081)	(0.000038)	(0.0300)	(0.0133)	------	------
5	1	AD70	= +6.621	−0.1235	−5.356	−0.0336	+0.0183	−0.0299	------	------	------	+0.532	+0.249	−0.000088	+0.0951	+0.0349	+7.07	0.1853
		s.d.	= (0.704)	(0.0126)	(1.101)	(0.0068)	(0.0025)	(0.0081)	------	------	------	(0.057)	(0.083)	(0.000038)	(0.0302)	(0.0136)	(4.41)	------
5A	2	AD70 (odd)	= +7.653	−0.1366	−6.346	−0.0317	+0.0153	−0.0360	------	------	------	+0.533	+0.258	−0.000118	+0.1206	+0.0355	*+5.88	0.1847
		s.d.	= (1.105)	(0.0177)	(1.753)	(0.0102)	(0.0035)	(0.0118)	------	------	------	(0.084)	(0.126)	(0.000052)	(0.0440)	(0.0190)	(7.06)	------
5B	3	AD70 (even)	= +5.453	−0.1076	−3.996	−0.0327	+0.0226	−0.0216	------	------	------	+0.484	+0.176	*−0.000017	+0.0658	+0.0432	*+4.97	0.1887
		s.d.	= (0.997)	(0.0204)	(1.520)	(0.0098)	(0.0039)	(0.0124)	------	------	------	(0.086)	(0.125)	(0.000066)	(0.0480)	(0.0211)	(6.34)	------
6	1	AD70	= +14.48	−0.1265	−5.412	------	------	------	−0.222	−0.300	−0.135	+0.420	+0.154	−0.000089	------	−0.0315	------	0.1865
		s.d.	= (1.14)	(0.0126)	(1.103)	------	------	------	(0.028)	(0.032)	(0.022)	(0.058)	(0.082)	(0.000037)	------	(0.0143)	------	------
7	1	AD70	= +14.31	−0.1252	−5.234	------	------	------	−0.221	−0.296	−0.136	+0.410	+0.185	−0.000081	------	−0.0357	+6.63	0.1858
		s.d.	= (1.14)	(0.0126)	(1.105)	------	------	------	(0.028)	(0.032)	(0.022)	(0.058)	(0.084)	(0.000038)	------	(0.0145)	(4.38)	------
7A	2	AD70 (odd)	= +14.57	−0.1405	−6.631	------	------	------	−0.198	−0.271	−0.138	+0.457	+0.208	−0.000108	------	−0.0292	+7.00	0.1864
		s.d.	= (1.62)	(0.0178)	(1.766)	------	------	------	(0.039)	(0.048)	(0.033)	(0.085)	(0.126)	(0.000052)	------	(0.0211)	(6.92)	------
7B	3	AD70 (even)	= +14.48	−0.1094	−3.935	------	------	------	−0.260	−0.333	−0.132	+0.327	*+0.089	*−0.000023	------	−0.0369	+3.80	0.1882
		s.d.	= (1.77)	(0.0203)	(1.511)	------	------	------	(0.045)	(0.048)	(0.030)	(0.086)	(0.127)	(0.000061)	------	(0.0213)	(6.27)	------

Note 1, 173 cements, Avg. = 4.433 × 10^6 psi, S.D. = 0.3223 × 10^6 psi
Note 2, 87 cements
Note 3, 86 cements
*Coef./s.d. ratio less than one.

TABLE 13–23. *Coefficients for equations relating AD70, the dynamic Young's modulus of elasticity in 10^6 psi after 14 days moist curing followed by 56 days drying in laboratory air of Series A concretes made of NAE cements, to various independent variables*

Eq. No.	Note	10^6 psi	Const.	Air content	w/c	C_3A	C_3S	C_4AF	SiO_2	Al_2O_3	Fe_2O_3	SO_3	K_2O	APF	Loss	MgO	Li	S.D.
1	1	AD70	= +4.518	−0.038														0.2998
		s.d.	= (0.038)	(0.027)														
2	1	AD70	= +4.126		*+0.520													0.3016
		s.d.	= (0.802)		(1.250)													
3	1	AD70	= +4.970	−0.047	*−0.683													0.3006
		s.d.	= (0.991)	(0.032)	(1.499)													
4	1	AD70	= +6.969	−0.1424	−5.610	−0.0354	+0.0181	−0.0319				+0.547	+0.228	−0.000088	+0.0891	+0.0382		0.1866
		s.d.	= (0.753)	(0.0234)	(1.183)	(0.0070)	(0.0025)	(0.0083)				(0.058)	(0.085)	(0.000039)	(0.0310)	(0.0137)		
5	1	AD70	= +6.871	−0.1517	−5.536	−0.0336	+0.0184	−0.0318				+0.538	+0.282	−0.000075	+0.0784	+0.0314	+9.09	0.1848
		s.d.	= (0.748)	(0.0237)	(1.173)	(0.0070)	(0.0025)	(0.0082)				(0.058)	(0.088)	(0.000039)	(0.0312)	(0.0140)	(4.59)	
5A	2	AD70 (odd)	= +7.112	−0.1287	−5.597	−0.0403	+0.0176	−0.0524				+0.542	+0.232	*−0.000051	+0.1141	*+0.0167	*+4.00	0.2028
		s.d.	= (1.115)	(0.0397)	(1.745)	(0.0119)	(0.0037)	(0.0147)				(0.094)	(0.141)	(0.000070)	(0.0623)	(0.0225)	(8.27)	
5B	2	AD70 (even)	= +6.763	−0.1737	−5.501	−0.0307	+0.0194	−0.0191				+0.520	+0.220	−0.000099	+0.0814	+0.0583	+9.81	0.1668
		s.d.	= (1.035)	(0.0305)	(1.620)	(0.0087)	(0.0038)	(0.0100)				(0.078)	(0.120)	(0.000048)	(0.0363)	(0.0199)	(5.91)	
6	1	AD70	= +14.61	−0.1490	−5.773				−0.218	−0.297	−0.138	+0.427	+0.171	−0.000082		−0.0321		0.1870
		s.d.	= (1.20)	(0.0234)	(1.185)				(0.029)	(0.033)	(0.022)	(0.059)	(0.085)	(0.000038)		(0.0146)		
7	1	AD70	= +14.47	−0.1570	−5.676				−0.217	−0.292	−0.141	+0.417	+0.221	−0.000071		−0.0381	+8.56	0.1855
		s.d.	= (1.19)	(0.0236)	(1.176)				(0.028)	(0.033)	(0.022)	(0.059)	(0.089)	(0.000038)		(0.0148)	(4.53)	
7A	2	AD70 (odd)	= +14.45	−0.1414	−5.853				−0.209	−0.301	−0.185	+0.445	+0.186	*−0.000033		−0.0536	*+5.36	0.2045
		s.d.	= (1.70)	(0.0388)	(1.752)				(0.041)	(0.046)	(0.038)	(0.097)	(0.139)	(0.000067)		(0.0242)	(7.56)	
7B	2	AD70 (even)	= +15.17	−0.1769	−5.670				−0.240	−0.309	−0.117	+0.376	+0.160	−0.000101		*−0.0161	+9.85	0.1653
		s.d.	= (1.78)	(0.0301)	(1.603)				(0.043)	(0.051)	(0.027)	(0.079)	(0.121)	(0.000048)		(0.0193)	(5.86)	

Note 1, 162 cements, Avg. = 4.460 × 10^6 psi, S.D. = 0.3008 × 10^6 psi
Note 2, 81 cements
*Coef./s.d. ratio less than one.

TABLE 13–24. *Calculated contributions of independent variables to AD70, the dynamic modulus after 14 days moist curing followed by 8 weeks in laboratory air of Series A concretes*

Independent variable	Range of variables (percent)	Coefficients from eq 5 table 13–23	Calculated contributions to AD70	Calculated range of contributions to AD70
			Const. = +6.87	
Air-content, NAE cements	0 to 4.5	−0.1517	0 to −0.68	0.68
w/c	0.6 to 0.7	−5.536	−0.33 to −0.39	0.06
C_3A	1 to 15	−0.0336	−0.03 to −0.50	0.47
C_3S	20 to 65	+0.0184	+0.37 to +1.20	0.83
C_4AF	1 to 16	−0.0318	−0.03 to −0.51	0.48
SO_3	1.2 to 3.0	+0.538	+0.65 to +1.61	0.96
K_2O	0 to 1.1	+0.282	0 to +0.31	0.31
APF**	*2500 to 5500	−0.000075	−0.19 to −0.41	0.22
Loss	0.3 to 3.3	+0.784	+0.24 to +2.59	2.35
MgO	0 to 5.0	+0.314	0 to +1.57	1.57
Li**	0 to 0.02	+9.09	0 to +0.18	0.18

*cm^2/g.
**Coefficient of doubtful significance as coef./s.d. ratio was less than 2.0.

the trace elements Cu, Zr, Ti, Rb, and Ba as independent variables in eq 3, caused a further significant reduction in variance, although the coefficients of the individual trace elements were not highly significant.

Equations calculated for the "odds" and "evens" in the array of cements, eqs 3A and 3B, indicated instances where fineness, Zr, Rb, and Ba had coef./s.d. ratios less than 1.0 in eq 3A.

The use of the major oxides in eqs 4, 5, and 6 resulted in S.D. values which were nearly the same as those obtained in eqs 2 and 3. The coef./s.d. ratio for Fe_2O_3 was greater than 1.0 in eq 5 but was less than 1.0 in eq 6. In eqs 5A and 5B calculated for the "odds" and "evens" the coef./s.d. ratios were less than 1.0 with SiO_2, CaO, fineness, Cu, Rb, and Ba in one or the other of the smaller lots of cements.

Using the independent variables of eq 3 of table 13–31, and the ranges of these variables, calculations were made of the estimated contributions to the dynamic modulus of the Series A concretes after 28 days resoaking and the ranges of these contributions. The calculated values are presented in table 13–32.

Higher values for air content, w/c, C_3A, C_4AF, were associated with lower values for dynamic modulus. Higher values for SO_3 and possibly C_3S and Zr were associated with higher dynamic modulus values. Variations of air content, w/c and SO_3 had the greatest calculated range of contributions to AD98.

6.5. Effect of Drying on Dynamic Modulus

6.5.1. Ratio of OD70 to OD14 for Series O Concretes (OE70/14)

The dynamic modulus was determined at 14 days after moist curing and again after drying in air for an additional 8 weeks. The frequency distribution of the ratios of dynamic modulus after drying to that before drying of the Series O concretes is presented in table 13–33. Concretes made of nine of the cements had higher dynamic modulus after the drying period but the majority of the concretes had lower values after the drying period than after the original 14 days in moist air. There was a broad distribution of results and an overlapping of the ratios for the concretes made of the different types of cement.

A series of equations for concretes made of AE + NAE cements is presented in table 13–34 indicating the independent variables associated with the dynamic modulus ratio. The use of commonly determined variables C_3A, Na_2O, SO_3, APF, Loss, and MgO in eq 1 resulted in a highly significant reduction in variance. (See table 13–57.) The additional use of the trace elements Rb, Zr, and Mn in eq 2 resulted in a reduction of variance, significant at the 5.0-percent level.

Calculations made for the "odds" and "evens" in the array of cements indicated that the coef./s.d. ratios for MgO, Rb, and Mn were less than 1.0 in eqs 2A or 2B.

Equations 3 and 4 were calculated using CaO and Al_2O_3 instead of C_3A and including also the air content. The use of the commonly determined variables resulted in a highly significant reduction in variance. The additional use of the trace elements as independent variables resulted in a

TABLE 13–25. *Frequency distribution of cements with respect to OD98, the dynamic modulus of elasticity of Series O concretes after storage of air-dried specimens in water for 28 days*

Type cement	Dynamic modulus of elasticity, 10^6 psi										
	3.8 to 4.0	4.0 to 4.2	4.2 to 4.4	4.4 to 4.6	4.6 to 4.8	4.8 to 5.0	5.0 to 5.2	5.2 to 5.4	5.4 to 5.6	5.6 to 5.8	Total
	Number of cements										
I					3	16	35	19	8	1	82
IA	1	3	3	1							8
II				1		10	29	22	5	1	68
IIA			1	1		1					3
III							8	9	3		20
IIIA			1	1		1					3
IV, V				1		4	6	4			15
Total	1	3	5	5	3	32	78	54	16	2	199

TABLE 13–26. *Coefficients for equations relating OD98, the dynamic Young's modulus of elasticity in 10^6 psi after air-dried specimens of Series O concretes made of AE + NAE cements were stored in water for 28 days, to various independent variables*

Eq. No.	Note	10^6 psi	Const.	Air content	C_3A	C_3S	C_4AF	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	APF	Loss	Ba	Cu	Zr	S.D.
1	1	OD98	= +5.22	−0.1401	−0.0124	+0.00593	−0.0155					+0.169	−0.000076	+0.0449				0.1267
		s.d.	= (0.12)	(0.0055)	(0.0041)	(0.00161)	(0.0053)					(0.035)	(0.000025)	(0.0199)				
2	1	OD98	= +5.25	−0.1400	−0.0152	+0.00601	−0.0142					+0.183	−0.000078	−0.0361	−0.663	−2.34	+0.619	0.1214
		s.d.	= (0.12)	(0.0052)	(0.0041)	(0.00154)	(0.0052)					(0.034)	(0.000024)	(0.0194)	(0.288)	(1.12)	(0.231)	
2A	2	OD98 (odd)	= +5.27	−0.1277	−0.0135	+0.00696	−0.0109					+0.152	−0.000097	+0.0443	−0.735	−3.45	* −0.535	0.1099
		s.d.	= (0.15)	(0.0062)	(0.0055)	(0.00185)	(0.0070)					(0.047)	(0.000029)	(0.0274)	(0.356)	(1.58)	(0.925)	
2B	3	OD98 (even)	= +5.31	−0.1585	−0.0173	+0.00421	−0.0214					+0.191	* −0.000036	* −0.0163	−0.639	* −1.12	+0.674	0.1303
		s.d.	= (0.19)	(0.0090)	(0.0060)	(0.00262)	(0.0083)					(0.051)	(0.000042)	(0.0308)	(0.474)	(1.61)	(0.266)	
3	1	OD98	= +4.70	−0.1394				+0.0286	−0.0378	−0.0649	−0.0304	+0.161	−0.000076	+0.0497				0.1270
		s.d.	= (0.84)	(0.0056)				(0.0096)	(0.0170)	(0.0199)	(0.0152)	(0.038)	(0.000025)	(0.0214)				
4	1	OD98	= +4.32	−0.1388				+0.0325	−0.0327	−0.0676	−0.0173	+0.181	−0.000080	+0.0455	−0.726	−2.56	+0.579	0.1213
		s.d.	= (0.83)	(0.0053)				(0.0095)	(0.0165)	(0.0191)	(0.0155)	(0.037)	(0.000024)	(0.0212)	(0.294)	(1.13)	(0.234)	
4A	2	OD98 (odd)	= +4.66	−0.1270				+0.0338	−0.0449	−0.0740	* −0.0133	+0.144	−0.000098	+0.0483	−0.746	−3.64	* −0.649	0.1104
		s.d.	= (1.05)	(0.0063)				(0.0120)	(0.0196)	(0.0247)	(0.0219)	(0.051)	(0.000029)	(0.0284)	(0.359)	(1.61)	(0.950)	
4B	3	OD98 (even)	= +3.71	−0.1563				+0.0306	* −0.0773	−0.0519	−0.0283	+0.203	* −0.000039	* +0.0346	−0.831	* −1.42	+0.600	0.1299
		s.d.	= (1.38)	(0.0091)				(0.0157)	(0.0287)	(0.0306)	(0.0244)	(0.055)	(0.000042)	(0.0346)	(0.500)	(1.63)	(0.273)	

*Coef./s.d. ratio less than one.
Note 1, 179 cements, Avg. 5.077 × 10^6 psi, S.D. = 0.2841 × 10^6 psi
Note 2, 90 cements
Note 3, 89 cements

TABLE 13–27. *Coefficients for equations relating OD98, the dynamic Young's modulus of elasticity in 10^6 psi after air dried specimens of Series O concretes made of NAE cements were stored in water for 28 days, to various independent variables*

Eq. No.	Note	10^6 psi	Const.	Air content	C_3A	C_3S	C_4AF	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	APF	Loss	Ba	Cu	Zr	S.D.
1	1	OD98	= +5.18	−0.1406	−0.0124	+0.00626	−0.0142					+0.184	−0.000080	+0.0474				0.1245
		s.d.	= (0.13)	(0.0133)	(0.0041)	(0.00162)	(0.0054)					(0.035)	(0.000025)	(0.0201)				
2	1	OD98	= +5.18	−0.1293	−0.0158	+0.00632	−0.0124					+0.197	−0.000081	+0.0397	−0.702	−2.47	+0.608	0.1186
		s.d.	= (0.12)	(0.0131)	(0.0041)	(0.00155)	(0.0052)					(0.034)	(0.000024)	(0.0195)	(0.285)	(1.11)	(0.277)	
2A	2	OD98 (odd)	= +5.24	−0.1241	−0.0133	+0.00554	−0.0139					+0.174	−0.000095	+0.0875	−0.838	−2.93	+1.483	0.1149
		s.d.	= (0.17)	(0.0178)	(0.0057)	(0.00196)	(0.0070)					(0.052)	(0.000030)	(0.0263)	(0.375)	(1.58)	(0.536)	
2B	3	OD98 (even)	= +5.05	−0.1373	−0.0154	+0.00777	−0.0094					+0.199	−0.000052	* −0.0174	−0.558	−2.41	+0.505	0.1207
		s.d.	= (0.19)	(0.0192)	(0.0061)	(0.00257)	(0.0083)					(0.048)	(0.000040)	(0.0300)	(0.446)	(1.71)	(0.258)	
3	1	OD98	= +4.51	−0.1393				+0.0311	−0.0381	−0.0650	−0.0252	+0.178	−0.000080	+0.0563				0.1247
		s.d.	= (0.84)	(0.0134)				(0.0096)	(0.0171)	(0.0201)	(0.0153)	(0.038)	(0.000025)	(0.0216)				
4	1	OD98	= +3.97	−0.1262				+0.0362	−0.0307	−0.0674	* −0.0081	+0.200	−0.000084	+0.0522	−0.795	−2.79	+0.558	0.1181
		s.d.	= (0.83)	(0.0132)				(0.0094)	(0.0166)	(0.0192)	(0.0157)	(0.037)	(0.000024)	(0.0212)	(0.291)	(1.14)	(0.229)	
4A	2	OD98 (odd)	= +4.98	−0.1237				+0.0251	−0.0391	−0.0692	−0.0252	+0.166	−0.000096	+0.0892	−0.848	−2.95	+1.475	0.1157
		s.d.	= (1.27)	(0.0180)				(0.0142)	(0.0213)	(0.0266)	(0.0227)	(0.061)	(0.000031)	(0.0278)	(0.381)	(1.60)	(0.543)	
4B	3	OD98 (even)	= +3.76	−0.1314				+0.0414	−0.0366	−0.0741	* −0.0021	+0.193	−0.000051	* −0.0007	−0.704	−3.03	+0.455	0.1205
		s.d.	= (1.22)	(0.0199)				(0.0138)	(0.0285)	(0.0294)	(0.0233)	(0.050)	(0.000040)	(0.0338)	(0.465)	(1.80)	(0.262)	

Note 1, 167 cements, Avg. = 5.136 × 10^6 psi, S.D. = 0.1752 × 10^6 psi
Note 2, 84 cements
Note 3, 83 cements
*Coef./s.d. ratio less than one.

Table 13–28. *Calculated contributions of independent variables to OD98, the dynamic modulus of Series O concretes after air dried specimens were stored in water for 28 days*

Independent variable	Range of variables (percent)	Coefficients from eq 2 table 13–27	Calculated contributions to OD98	Calculated range of contributions to OD98
			Const. = +5.18	
Air-content, NAE cements	0 to 4.5	−0.1293	0 to −0.58	0.58
C_3A	1 to 15	−0.0158	−0.02 to −0.24	0.22
C_3S	20 to 65	+0.00632	+0.13 to +0.41	0.28
C_4AF	1 to 16	−0.0124	−0.01 to −0.20	0.19
SO_3	1.2 to 3.0	+0.197	+0.24 to +0.59	0.35
APF	*2500 to 5500	−0.000081	−0.20 to −0.45	0.25
Loss	0.3 to 3.3	+0.0397	+0.01 to +0.13	0.12
Ba	0 to 0.02	−0.702	0 to −0.14	0.14
Cu	0 to 0.05	−2.47	0 to −0.12	0.12
Zr	0 to 0.5	+0.608	0 to +0.31	0.31

*cm^2/g.

reduction of variance significant at the 5.0-percent level.

A corresponding series of equations calculated for the Series O concretes made of NAE cements is presented in table 13–35. The coefficient and coef./s.d. ratio for air content of concretes made of NAE cements were greater in magnitude and appeared somewhat more significant than in the previous table where the AE cements were included although there were instances (eqs 2A and 4A) where the coef./s.d. ratio was less than 1.0. The coef./s.d. ratios of CaO, fineness, Rb, Zr, and Mn were also less than one in 1.0 or both of the equations calculated for the "odds" or "evens" in the array of cements.

Using the coefficients of the independent variables of eq 2, table 13–35, and the ranges of these variables, computations were made of the esti-

Table 13–29. *Frequency distribution of cements with respect to AD98, the dynamic modulus of elasticity of Series A concretes after storage of air-dried specimens in water for 28 days*

Type cement	Dynamic modulus of elasticity, 10^6 psi										
	4.0 to 4.2	4.2 to 4.4	4.4 to 4.6	4.6 to 4.8	4.8 to 5.0	5.0 to 5.2	5.2 to 5.4	5.4 to 5.6	5.6 to 5.8	5.8 to 6.0	Total
	Number of cements										
I				4	22	35	14	2	1	1	79
IA	1		3	4							8
II				2	10	25	22	8			67
IIA		1			2						3
III					5	3	11		1		20
IIIA				1	1		1				3
IV, V			1		2	9	3				15
Total	1	1	4	11	42	72	51	10	2	1	195

Table 13–30. *Coefficients for equations relating AD98, the dynamic Young's modulus NAE cements were stored in water for 28*

Eq. No.	Note	10^6 psi	Const.	Air content	w/c	C_3A	C_3S	C_4AF	CaO
1	1	AD98 s.d.	= +8.814 = (0.450)	−0.1134 (0.0080)	−5.499 (0.687)				
2	1	AD98 s.d.	= +9.501 = (0.455)	−0.1298 (0.0083)	−6.754 (0.717)	−0.0146 (0.0043)	+0.00468 (0.00159)	−0.0194 (0.0053)	
3	1	AD98 s.d.	= +9.589 = (0.445)	−0.1285 (0.0080)	−6.795 (0.694)	−0.0179 (0.0043)	+0.00475 (0.00153)	−0.0166 (0.0052)	
3A	2	AD98 (odd) s.d.	= +11.170 = (0.728)	−0.1504 (0.0116)	−9.106 (1.148)	−0.0192 (0.0079)	+0.00524 (0.00221)	−0.0268 (0.0081)	
3B	3	AD98 (even) s.d.	= +8.108 = (0.573)	−0.1033 (0.0119)	−4.633 (0.892)	−0.0190 (0.0056)	+0.00445 (0.00220)	−0.0097 (0.0079)	
4	1	AD98 s.d.	= +10.216 = (0.888)	−0.1303 (0.0083)	−6.739 (0.718)				+0.0130 (0.0092)
5	1	AD98 s.d.	= +8.672 = (0.721)	−0.1242 (0.0077)	−6.562 (0.687)				+0.0262 (0.0084)
5A	2	AD98 (odd) s.d.	= +9.822 = (1.180)	−0.1427 (0.0118)	−8.490 (1.182)				+0.0276 (0.0131)
5B	3	AD98 (even) s.d.	= +7.181 = (1.018)	−0.1026 (0.0111)	−4.726 (0.875)				+0.0263 (0.0114)
6	1	AD98 s.d.	= +9.699 = (0.872)	−0.1287 (0.0081)	−6.693 (0.702)				**+0.0181 (0.0091)

Note 1, 173 cements, Avg. = 5.080 × 10^6 psi, S.D. = 0.2146 × 10^6 psi
Note 2, 87 cements
Note 3, 86 cements

*Coef./s.d. ratio less than 1.
**Coef./s.d. ratio less than 1 in "odds" or "evens".

mated contributions to the dynamic modulus ratio and the calculated range of these contributions. The results of these calculations are presented in table 13–36. Higher C_3A, and possibly Na_2O, fineness, and Zr were associated with lower values for the OE70/14 ratio. Higher values for SO_3 and loss on ignition were associated with higher values for the ratio.

6.5.2. Ratio of OD70 to OD14 for Series A Concretes (OE70/14)

The frequency distribution of the ratio of the dynamic modulus of Series A concretes after drying for 8 weeks to the dynamic modulus after the initial 14-day moist curing is presented in table 13–37. Twelve of the concretes made of the 195 cements had higher dynamic modulus values after drying in laboratory air whereas most had lower values after than before the dry storage. There was a broad distribution of values and an overlapping of values obtained with the different types of cement.

A series of equations for concretes made of AE + NAE cements is presented in table 13–38 to indicate the variables associated with the dynamic modulus ratio of the Series A concretes. The use of the commonly determined variables, C_3A, C_4AF, SO_3, Na_2O, MgO, APF, and Loss in eq 1 resulted in a highly significant reduction in variance. (See table 13–57.) The additional use in eq 2 of the trace elements Co, Rb, and Mn resulted in a reduction of variance significant at the 5.0-percent level although none of the coefficients for the individual trace elements was highly significant.

The use of CaO, Al_2O_3 and Fe_2O_3 together with the other commonly determined variables in eqs 3 and 4 resulted in S.D. values which were about the same as those obtained in eqs 1 and 2 where the calculated potential compounds were used.

Equations calculated for the "odds" and "evens" in the array of cements indicated that the coef./s.d. ratios were less than 1.0 for C_4AF, CaO, Fe_2O_3, Co, Rb, and Mn in one or the other of the smaller lots of cement. (See eqs 2A, 2B, 4A, and 4B.)

A series of equations calculated for the Series A concretes made of NAE cements is presented in table 13–39. As was the case with the Series O

of elasticity in 10^6 psi after air-dried specimens of Series A concretes made of AE + days, to various independent variables

SiO_2	Al_2O_3	Fe_2O_3	SO_3	APF	Cu	Zr	Ti	Rb	Ba	S.D.
----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	0.1423
----------	----------	----------	+0.216 (0.035)	−0.000053 (0.000023)	----------	----------	----------	----------	----------	0.1230
----------	----------	----------	+0.204 (0.035)	−0.000051 (0.000022)	−3.02 (1.08)	+0.541 (0.222)	−0.165 (0.080)	+ 8.60 (5.04)	−0.428 (0.284)	0.1166
----------	----------	----------	+0.254 (0.053)	−0.000073 (0.000033)	−3.89 (1.64)	+0.450 (0.250)	−0.161 (0.099)	*+8.15 (8.16)	−0.644 (0.428)	0.1206
----------	----------	----------	+0.129 (0.049)	*−0.000008 (0.000034)	−2.42 (1.51)	+0.733 (0.571)	−0.183 (0.150)	+11.53 (6.59)	*−0.254 (0.455)	0.1085
−0.0459 (0.0163)	−0.0815 (0.0197)	−0.0469 (0.0150)	+0.189 (0.038)	−0.000055 (0.000023)	----------	----------	----------	----------	----------	0.1231
−0.0280 (0.0155)	−0.0701 (0.0190)	----------	+0.200 (0.037)	−0.000049 (0.000023)	−3.69 (1.05)	+0.547 (0.224)	−0.189 (0.081)	+8.93 (5.10)	−0.450 (0.289)	0.1177
−0.0288 (0.0225)	−0.0718 (0.0312)	----------	+0.251 (0.060)	−0.000063 (0.000034)	−4.66 (1.75)	+0.475 (0.263)	−0.171 (0.105)	+8.70 (8.66)	−0.601 (0.462)	0.1266
*−0.0187 (0.0225)	−0.0647 (0.0247)	----------	+0.134 (0.052)	*−0.000005 (0.000033)	−2.35 (1.33)	+0.706 (0.566)	−0.194 (0.144)	+11.50 (6.55)	*−0.219 (0.449)	0.1078
**−0.0405 (0.0159)	−0.0853 (0.0193)	**−0.0314 (0.0153)	+0.197 (0.037)	**−0.000052 (0.000023)	−2.81 (1.11)	+0.479 (0.223)	----------	**+8.04 (5.11)	**−0.489 (0.289)	0.1182

TABLE 13–31. *Coefficients for equations relating AD98, the dynamic Young's modulus cements were stored in water for 28 d*

Eq. No.	Note	10^6 psi	Const.	Air content	w/c	C_3A	C_3S	C_4AF	CaO
1	1	AD98 s.d.	= +8.749 = (0.477)	−0.1075 (0.0156)	−5.412 (0.722)	----------	----------	----------	----------
2	1	AD98 s.d.	= +9.703 = (0.494)	−0.1396 (0.0154)	−7.118 (0.778)	−0.0137 (0.0044)	+0.00463 (0.00164)	−0.0195 (0.0054)	----------
3	1	AD98 s.d.	= +9.712 = (0.475)	−0.1276 (0.0150)	−7.051 (0.743)	−0.0173 (0.0044)	+0.00468 (0.00157)	−0.0160 (0.0053)	----------
3A	2	AD98 (odd) s.d.	= +10.001 = (0.609)	−0.1215 (0.0204)	−7.531 (0.971)	−0.0266 (0.0067)	+0.00329 (0.00220)	−0.0294 (0.0084)	----------
3B	2	AD98 (even) s.d.	= +9.274 = (0.684)	−0.1391 (0.0203)	−6.315 (1.054)	−0.0142 (0.0057)	+0.00410 (0.00237)	−0.0081 (0.0069)	----------
4	1	AD98 s.d.	= +10.216 = (0.924)	−0.1397 (0.0155)	−7.101 (0.780)	----------	----------	----------	+0.0145 (0.0095)
5	1	AD98 s.d.	= +9.565 = (0.908)	−0.1311 (0.0152)	−6.951 (0.755)	----------	----------	----------	+0.0203 (0.0094)
5A	2	AD98 (odd) s.d.	= +8.161 = (1.212)	−0.1195 (0.0200)	−7.667 (0.961)	----------	----------	----------	+0.0316 (0.0137)
5B	2	AD98 (even) s.d.	= +10.611 = (1.382)	−0.1495 (0.0223)	−5.971 (1.148)	----------	----------	----------	*+0.0103 (0.0134)
6	1	AD98 s.d.	= +8.527 = (0.731)	−0.1196 (0.0141)	−6.850 (0.727)	----------	----------	----------	+0.0282 (0.0085)

Note 1, 162 cements, Avg. = 5.112 × 10^6 psi, S.D. = 0.1716 × 10^6 psi.
Note 2, 81 cements
*Coef./s.d. ratio less than one.
**Coef./s.d. ratio less than one in "odds" or "evens".

TABLE 13–32. *Calculated contributions of independent variables to AD98, the dynamic modulus of Series A concretes after the air-dried specimens were stored in water for 28 days*

Independent variable	Range of variables (percent)	Coefficients from eq 3 table 13–31	Calculated contributions to AD98	Calculated range of contributions to AD98
			Const. = +9.712	
Air-content, NAE cements	0 to 4.5	−0.1276	0 to −0.57	0.57
w/c	0.6 to 0.7	−7.051	−4.23 to −4.94	0.71
C_3A	1 to 15	−0.0173	−0.02 to −0.25	0.23
C_3S	20 to 65	+0.00468	+0.09 to +0.30	0.21
C_4AF	1 to 16	−0.0160	−0.02 to −0.26	0.24
SO_3	1.2 to 3.0	+0.209	+0.25 to +0.63	0.38
APF**	*2500 to 5500	−0.000042	−0.10 to −0.23	0.13
Cu	0 to 0.05	−3.09	0 to −0.15	0.15
Zr	0 to 0.5	+0.581	0 to +0.29	0.29
Ti	0 to 1.0	−0.189	0 to −0.19	0.19
Rb**	0 to 0.01	+8.10	0 to +0.08	0.08
Ba**	0 to 0.02	−0.460	0 to −0.01	0.01

*cm^2/g.
**Coefficient of doubtful significance as coef./s.d. ratio was less than 2.0.

concretes, the coefficients of the air content of the concretes made with NAE cements are probably significant, which was not evident when the AE cements were included. The use of commonly determined variables in eqs 1 and 3 resulted in a highly significant reduction in variance. (See table 13–57.) The additional use of the trace elements Co, Rb, and Mn in eq 2 resulted in a reduction of variance significant at the 5.0 percent probability level. In eq 3, CaO had a coef./s.d. ratio greater than 1.0 but the ratio was less than 1.0 in eq 4; therefore an evaluation of the reduction of variance was not made.

With the use of the coefficients of the independent variables of eq 2 table 13–39 and the ranges of these variables, computations were made of the estimated contributions to the AE70/14 ratio. These computed values are presented in table 13–40 together with the calculated ranges of the contributions. Higher values for C_3A, Na_2O, and probably air content, and fineness were associated

of elasticity in 10^6 psi after air dried specimens of Series A concretes made of NAE ays, to various independent variables

SiO₂	Al₂O₃	Fe₂O₃	SO₃	APF	Cu	Zr	Ti	Rb	Ba	S.D.
										0.1448
			+0.224 (0.035)	−0.000045 (0.000024)						0.1240
			+0.209 (0.035)	−0.000042 (0.000023)	−3.09 (1.12)	+0.581 (0.224)	−0.189 (0.083)	+8.10 (5.22)	−0.460 (0.288)	0.1168
			+0.267 (0.050)	*−0.000009 (0.000036)	−5.24 (1.61)	*+0.204 (1.884)	+0.169 (0.137)	*+7.02 (7.03)	*−0.169 (0.870)	0.1134
			+0.176 (0.050)	−0.000045 (0.000030)	−2.13 (1.49)	+0.639 (0.217)	−0.459 (0.116)	+10.26 (7.31)	*−0.058 (0.323)	0.1081
−0.0428 (0.0169)	−0.0759 (0.0205)	−0.0469 (0.0156)	+0.201 (0.039)	−0.000046 (0.000024)						0.1243
−0.0367 (0.0164)	−0.0802 (0.0199)	−0.0293 (0.0160)	+0.209 (0.039)	−0.000043 (0.000024)	−2.85 (1.15)	+0.497 (0.225)		+8.05 (5.32)	−0.524 (0.296)	0.1189
*−0.0006 (0.0212)	−0.0667 (0.0233)	−0.0299 (0.0226)	+0.277 (0.052)	*−0.000003 (0.000035)	−5.92 (1.62)	*+0.670 (1.669)		+9.29 (7.10)	*−0.461 (0.856)	0.1120
−0.0687 (0.0275)	−0.1052 (0.0350)	−0.0333 (0.0228)	+0.129 (0.059)	−0.000058 (0.000033)	*−0.55 (1.60)	+0.465 (0.231)		+11.48 (8.03)	*−0.210 (0.352)	0.1181
**−0.0227 (0.0159)	−0.0633 (0.0196)		+0.210 (0.038)	**−0.000040 (0.000023)	−3.80 (1.06)	**+0.591 (0.225)	**−0.225 (0.084)	+8.11 (5.26)	**−0.517 (0.292)	0.1174

TABLE 13–33. *Frequency distribution of cements with respect to OE 70/14, the ratio of dynamic modulus of Series O concretes determined after 8 weeks in laboratory air divided by the values after the original 14 days of moist curing*

Type cement	Dynamic E ratio											
	0.82 to 0.84	0.84 to 0.86	0.86 to 0.88	0.88 to 0.90	0.90 to 0.92	0.92 to 0.94	0.94 to 0.96	0.96 to 0.98	0.98 to 1.00	1.00 to 1.02	1.02 to 1.04	Total
	Number of cements											
I	2	4	11	10	13	12	17	7	6			82
IA				2		3		2			1	8
II	2	2	7	5	8	16	9	8	8	1	2	60
IIA					1	1	1					3
III			1	1	2	2	2	5	5	2		20
IIIA							1	1		1		3
IV, V				2	1	2	4	1	3	2		15
Total	4	6	19	20	25	36	34	24	22	6	3	191

TABLE 13–34. *Coefficients for equations relating OE 70/14, the ratio of dynamic Young's modulus of elasticity at 70 days (after drying in air) to that at 14 days (after moist curing) of Series O concretes made with AE + NAE cements, to various independent variables*

Eq. No.	Note		Const.	C_3A	CaO	Al_2O_3	Na_2O	SO_3	APF	Loss	MgO	Rb	Zr	Mn	Air content	S.D.
1	1	OE 70/14	= +0.871	−0.00605			−0.0458	+0.0702	−0.0000147	+0.0252	+0.00354					0.03232
		s.d.	= (0.019)	(0.00086)			(0.0148)	(0.0088)	(0.0000058)	(0.0051)	(0.00208)					
2	1	OE 70/14	= +0.880	−0.00587			−0.0385	+0.0698	−0.0000170	+0.0259	+0.00225	−2.14	−0.134	+0.0324		0.03167
		s.d.	= (0.019)	(0.00085)			(0.0149)	(0.0087)	(0.0000058)	(0.0051)	(0.00210)	(1.30)	(0.063)	(0.0203)		
2A	2	OE 70/14 (odd)	= +0.911	−0.00560			−0.0425	+0.0612	−0.0000197	+0.0257	*+0.00022	−3.25	−0.140	+0.0345		0.03247
		s.d.	= (0.027)	(0.00136)			(0.0202)	(0.0139)	(0.0000075)	(0.0076)	(0.00308)	(1.92)	(0.070)	(0.0260)		
2B	3	OE 70/14 (even)	= +0.849	−0.00575			−0.0311	+0.0732	−0.0000133	+0.0277	+0.00477	*−1.07	−0.191	*+0.0295		0.03191
		s.d.	= (0.029)	(0.00119)			(0.0239)	(0.0122)	(0.0000097)	(0.0078)	(0.00304)	(1.89)	(0.174)	(0.0356)		
3	1	OE 70/14	= +1.270		−0.00535	−0.0181	−0.0492	+0.0685	−0.0000132	+0.0214					−0.00148	0.03248
		s.d.	= (0.145)		(0.00225)	(0.0028)	(0.0151)	(0.0092)	(0.0000061)	(0.0052)					(0.00139)	
4	1	OE 70/14	= +1.206		−0.00426	−0.0177	−0.0403	+0.0690	−0.0000162	+0.0228		−2.27	−0.136	+0.0345	−0.00170	0.03172
		s.d.	= (0.150)		(0.00233)	(0.0028)	(0.0153)	(0.0090)	(0.0000060)	(0.0053)		(1.34)	(0.063)	(0.0208)	(0.00137)	
4A	2	OE 70/14 (odd)	= +1.267		−0.00481	−0.0165	−0.0484	+0.0582	−0.0000192	+0.0239		−3.46	−0.128	+0.0335	*−0.00160	0.03251
		s.d.	= (0.216)		(0.00337)	(0.0045)	(0.0203)	(0.0149)	(0.0000083)	(0.0078)		(2.04)	(0.070)	(0.0267)	(0.00193)	
4B	3	OE 70/14 (even)	= +1.147		−0.00378	−0.0175	−0.0267	+0.0724	−0.0000114	+0.0238		*+1.52	−0.258	*+0.0318	*−0.00184	0.03237
		s.d.	= (0.226)		(0.00348)	(0.0038)	(0.0252)	(0.0124)	(0.0000097)	(0.0079)		(1.93)	(0.176)	(0.0372)	(0.00207)	

Note 1, 179 cements, Avg. = 0.9307, S.D. = 0.04385
Note 2, 90 cements
Note 3, 89 cements
*Coef./s.d. ratio less than one.

TABLE 13–35. *Coefficients for equations relating OE 70/14, the ratio of dynamic Young's modulus of elasticity at 70 days (after drying in air) to that at 14 days (after moist curing) of Series O concretes made with NAE cements, to various independent variables*

Eq. No.	Note		Const.	C_3A	CaO	Al_2O_3	Na_2O	SO_3	APF	Loss	MgO	Rb	Zr	Mn	Air content	S.D.
1	1	OE 70/14	= +0.886	−0.00581			−0.0422	+0.0724	−0.0000149	+0.0209	+0.00388				−0.01061	0.03152
		s.d.	= (0.019)	(0.00086)			(0.0150)	(0.0088)	(0.0000058)	(0.0051)	(0.00209)				(0.00340)	
2	1	OE 70/14	= +0.894	−0.00573			−0.0343	+0.0719	−0.0000171	+0.0223	+0.00269	−1.37	−0.136	+0.0288	−0.01012	0.03102
		s.d.	= (0.020)	(0.00086)			(0.0151)	(0.0088)	(0.0000058)	(0.0051)	(0.00213)	(1.32)	(0.062)	(0.0207)	(0.00343)	
2A	2	OE 70/14 (odd)	= +0.911	−0.00488			−0.0517	+0.0718	−0.0000228	+0.0186	*−0.00093	−2.48	−0.119	*+0.0177	*−0.00195	0.03057
		s.d.	= (0.027)	(0.00130)			(0.0198)	(0.0146)	(0.0000074)	(0.0071)	(0.00323)	(1.83)	(0.065)	(0.0273)	(0.00465)	
2B	3	OE 70/14 (even)	= +0.879	−0.00578			−0.0336	+0.0701	*−0.0000081	+0.0197	+0.00485	*+0.27	*−0.561	+0.0474	−0.01873	0.03126
		s.d.	= (0.031)	(0.00118)			(0.0251)	(0.0118)	(0.0000098)	(0.0082)	(0.00301)	(1.97)	(0.617)	(0.0319)	(0.00517)	
3	1	OE 70/14	= +1.246		−0.00469	−0.0180	−0.0461	+0.0711	−0.0000141	+0.0175					−0.01173	0.03148
		s.d.	= (0.143)		(0.00220)	(0.0027)	(0.0151)	(0.0091)	(0.0000061)	(0.0052)					(0.00336)	
4	1	OE 70/14	= +1.168		−0.00338	−0.0182	−0.0361	+0.0710	−0.0000170	+0.0197		*−1.15	−0.144	+0.0345	−0.01140	0.03087
		s.d.	= (0.148)		(0.00230)	(0.0028)	(0.0153)	(0.0090)	(0.0000060)	(0.0052)		(1.35)	(0.062)	(0.0211)	(0.00339)	
4A	2	OE 70/14 (odd)	= +1.115		*−0.00232	−0.0172	−0.0479	+0.0678	−0.0000233	+0.0185		−2.39	−0.128	*+0.0244	*−0.00294	0.02975
		s.d.	= (0.203)		(0.00316)	(0.0040)	(0.0192)	(0.0142)	(0.0000078)	(0.0068)		(1.82)	(0.064)	(0.0274)	(0.00452)	
4B	3	OE 70/14 (even)	= +1.163		*−0.00354	−0.0178	−0.0348	+0.0700	*−0.0000074	+0.0177		*+0.74	*−0.530	+0.0516	−0.02064	0.03192
		s.d.	= (0.230)		(0.00355)	(0.0039)	(0.0271)	(0.0123)	(0.0000101)	(0.0087)		(2.07)	(0.626)	(0.0330)	(0.00519)	

Note 1, 167 cements, Avg. = 0.9295, S.D. = 0.04400
Note 2, 84 cements
Note 3, 83 cements
*Coef./s.d. ratio less than one.

TABLE 13–36. *Calculated contributions of independent variables to OE70/14, the ratio of dynamic modulus of Series O concretes after drying in air for 8 weeks divided by the dynamic modulus after the original 14-day moist curing*

Independent variable	Range of variables (percent)	Coefficients from eq 2 table 13–35	Calculated contributions to OE70/14	Calculated range of contributions to OE70/14
			Const. = +0.894	
C_3A	1 to 15	−0.00573	−0.006 to −0.086	0.080
Na_2O	0 to 0.7	−0.0343	0 to −0.024	0.024
SO_3	1.2 to 3.0	+0.0719	+0.086 to +0.216	0.130
APF	*2500 to 5500	−0.0000171	−0.043 to −0.094	0.051
Loss	0.3 to 3.3	+0.0223	+0.007 to +0.074	0.067
MgO**	0 to 5.0	+0.00269	0 to +0.013	0.013
Rb**	0 to 0.01	−1.37	0 to −0.014	0.014
Zr	0 to 0.5	−0.136	0 to −0.068	0.068
Mn**	0 to 1.0	+0.0288	0 to +0.029	0.029
Air-content, NAE cements	0 to 4.5	−0.01012	0 to −0.046	0.046

*cm^2/g.
**Coefficient of doubtful significance as coef./s.d. ratio was less than 2.0.

with lower values for AE70/14. Higher values for SO_3 and loss on ignition were associated with higher values for the AE70/14 ratio.

6.6. Effect of Rewetting on Dynamic Modulus

6.6.1. Ratio of 98-Day (Wet) to 70-Day (Dry) Dynamic Modulus of Series O Concretes

After drying in laboratory air for 8 weeks, the dynamic modulus was determined (total age 70 days). The specimens were then placed in water and the dynamic modulus was again determined after 4 weeks (total age 98 days). The ratio of the dynamic modulus values OE98/70 was calculated and the frequency distribution of this ratio for the Series O concretes is presented in table 13–41. The concretes made with all of the cements showed some increase in dynamic modulus due to the

TABLE 13–37. *Frequency distribution of cements with respect to AE 70/14, the ratio of dynamic modulus of Series A concretes determined after 8 weeks in laboratory air divided by the values after the original 14 days of moist curing*

Type cement	Dynamic *E* ratio										
	0.82 to 0.84	0.84 to 0.86	0.86 to 0.88	0.88 to 0.90	0.90 to 0.92	0.92 to 0.94	0.94 to 0.96	0.96 to 0.98	0.98 to 1.00	1.00 to 1.02	Total
	Number of cements										
I	1	5	8	12	13	19	12	5	4		79
IA				1	1	1	2		1	2	8
II	3		4	8	11	11	11	6	10	3	67
IIA					1	1	1				3
III			2		3	2	3	3	5	2	20
IIIA							1	1		1	3
IV, V			1	1	1	1	4	3		4	15
Total	4	5	15	22	30	35	34	18	20	12	195

TABLE 13–38. *Coefficients for equations relating AE 70/14, the ratio of dynamic Young's modulus of elasticity at 70 days (after drying in air) to that at 14 days (after moist curing) with Series A concretes made of AE + NAE cements, to various independent variables*

Eq. No.	Note		Const.	C_3A	C_4AF	CaO	Al_2O_3	Fe_2O_3	SO_3	Na_2O	MgO	APF	Loss	Co	Rb	Mn	S.D.
1	1	AE 70/14	= +0.905	−0.00768	−0.00137	------	------	------	+0.0702	−0.0452	+0.0044	−0.0000160	+0.0216	------	------	------	0.03210
		s.d.	= (0.027)	(0.00106)	(0.00133)	------	------	------	(0.0091)	(0.0149)	(0.0021)	(0.0000059)	(0.0052)	------	------	------	------
2	1	AE 70/14	= +0.904	−0.00741	−0.00173	------	------	------	+0.0722	−0.0434	+0.0037	−0.0000166	+0.0203	+2.59	−2.45	+0.0396	0.03146
		s.d.	= (0.027)	(0.00107)	(0.00134	------	------	------	(0.0090)	(0.0147)	(0.0021)	(0.0000059)	(0.0051)	(1.74)	(1.35)	(0.0207)	------
2A	2	AE 70/14 (odd)	= +0.869	−0.00818	* −0.00092	------	------	------	+0.0817	−0.0264	+0.0037	−0.0000143	+0.0203	+4.38	* −1.93	+0.0483	0.03130
		s.d.	= (0.040)	(0.00165)	(0.00209)	------	------	------	(0.0135)	(0.0222)	(0.0031)	(0.0000074)	(0.0074)	(2.66)	(2.08)	(0.0248)	------
2B	3	AE 70/14 (even)	= +0.926	−0.00691	−0.00257	------	------	------	+0.0687	−0.0515	+0.0035	−0.0000172	+0.0168	* +0.91	−2.41	* +0.0326	0.03294
		s.d.	= (0.038)	(0.00157)	(0.00193)	------	------	------	(0.0140)	(0.0212)	(0.0034)	(0.0000108)	(0.0085)	(2.65)	(1.95)	(0.0433)	------
3	1	AE 70/14	= +1.207	------	------	−0.00435	−0.0206	+0.00548	+0.0678	−0.0494	------	−0.0000140	+0.0186	------	------	------	0.03219
		s.d.	= (0.167)	------	------	(0.00246)	(0.0028)	(0.00369)	(0.0094)	(0.0151)	------	(0.0000062)	(0.0053)	------	------	------	------
4	1	AE 70/14	= +1.190	------	------	−0.00415	−0.0198	+0.00418	+0.0698	−0.0475	------	−0.0000147	+0.0175	+2.71	−2.67	+0.0392	0.03147
		s.d.	= (0.168)	------	------	(0.00250)	(0.0029)	(0.00366)	(0.0093)	(0.0150)	------	(0.0000061)	(0.0053)	(1.36)	(1.36)	(0.0208)	------
4A	2	AE 70/14 (odd)	= +1.287	------	------	−0.00617	−0.0217	+0.00747	+0.0766	−0.0347	------	−0.0000108	+0.0167	+4.52	−2.52	+0.0457	0.03094
		s.d.	= (0.236)	------	------	(0.00351)	(0.0043)	(0.00559)	(0.0140)	(0.0228)	------	(0.0000077)	(0.0074)	(2.62)	(2.11)	(0.0243)	------
4B	3	AE 70/14 (even)	= +1.084	------	------	* −0.00224	−0.0181	* +0.00135	+0.0674	−0.0540	------	−0.0000158	+0.0144	* +1.29	−2.59	* +0.0333	0.03310
		s.d.	= (0.269)	------	------	(0.00396)	(0.0042)	(0.00553)	(0.0144)	(0.0213)	------	(0.0000110)	(0.0086)	(2.62)	(1.96)	(0.0443)	------

Note 1, 171 cements, Avg. = 0.09311, S.D. = 0.04347
Note 2, 86 cements
Note 3, 85 cements
*Coef./s.d. ratio less than 1.

soaking. There was, however, a fairly broad distribution of values and an overlapping of the values obtained with the different types of cement.

A series of equations is presented in table 13–42 to indicate the independent variables associated with the 98-day/70-day dynamic modulus ratio of Series O concretes made with AE + NAE cements. The use of air content, C_3A, C_3A/SO_3, C_3S, C_4AF, K_2O, Loss, and MgO as independent variables in eq 1 resulted in a highly significant reduction in variance. With the additional use of the trace elements Co, Li, Zr, and P in eq 2 there was a further significant reduction of the S.D. value. (See table 13–57.)

The use of CaO and SiO_2 together with Al_2O_3/SO_3 instead of the calculated potential compounds in eq 3 also resulted in a significant reduction in variance. In eq 4 the use of the trace elements caused a reduction of variance significant at the 5.0-percent level.

Equations calculated for the "odds" and "evens" in the array of cements (eqs 2A, 2B, 4A, and 4B) show instances where the coef./s.d. ratio was less than 1.0 for C_4AF, K_2O, MgO, Co, and P in one or both of the equations for the smaller lots of cement.

A corresponding series of equations for the ratio of dynamic modulus after to that before resoaking for the Series O concretes made of NAE cements is presented in table 13–43. The coefficients for the independent variables as well as the coef./s.d. ratios were in reasonable agreement with those of the previous table where the AE cements were included.

Using the coefficients of the independent variables in eq 2 table 13–43 as well as the ranges of these variables, calculations were made of the estimated contributions to the ratio of dynamic-modulus values after to that before resoaking and the ranges of these contributions. The calculated values are presented in table 13–44. Higher values for air content and C_3A/SO_3 were associated with higher values for the dynamic-modulus ratio. Higher values for C_3A, C_3S, and possibly K_2O, Loss, MgO, and Li were associated with lower values for the dynamic-modulus ratio. Variations of C_3A, C_3A/SO_3 and C_3S had the greatest effect on the calculated range of contributions to OE98/70.

6.6.2. Ratio of 98-Day (Wet) to 70-Day (Dry) Dynamic Modulus of Series A Concretes

The frequency distribution of the ratio of dynamic modulus after to that before resoaking for Series A concretes is presented in table 13–45. Concretes made of all of the cements increased in dynamic modulus with the increase ranging from less than 5 to more than 40 percent. There was an overlapping of the values obtained with the different types of cement.

A series of equations indicating the independent variables associated with the OE98/70 dynamic-modulus ratio of Series A concretes made with AE + NAE cements is presented in table 13–46. The use of the air content, C_3A, C_3S, C_4AF, SO_3, K_2O, Loss, and MgO in eq 1 resulted in a highly significant reduction of variance. (See table 13–57.) With the addition of C_3A/SO_3 as an independent variable in eq 2 the sign of the coefficient for C_3A became negative and the coef./s.d. ratio for SO_3 became less than 1.0. Deleting SO_3 as an independent variable in eq 3 resulted in higher coef./s.d. ratios for both C_3A and C_3A/SO_3. The interrelation between these independent variables is obvious and has been discussed in previous sections. The use of the trace elements Li, P, and Co in eq 4 together with the commonly determined variables resulted in a significant reduction in variance. (See table 13–57.) Equations 5 and 6 were calculated using CaO and SiO_2 in place of C_3A, C_3S, and C_4AF. There was a significant reduction in variance in both equations.

In equations calculated for the smaller lots of cement, C_4AF, P, and Co had coef./s.d. ratios less than 1.0 in eq 4B, and P and Co had coef./s.d. ratios less than 1.0 in eq 6B.

With the use of only the NAE cements, equations were calculated to determine the variables associated with the OE98/70 dynamic-modulus ratio. The results are presented in table 13–47. There was a reasonable agreement of the coefficients and coef./s.d. ratios with those of the previous table where the AE cements were included. There were instances in the equations for the "odds" and "evens" where air content, MgO, P, and Co had coef./s.d. ratios less than 1.0 in the smaller lots of cement.

Using the coefficients of the independent variables of eq 4 table 13–47, calculations were made of the estimated contributions to the AE 98/70 dynamic-modulus ratio. These calculated values together with the calculated ranges of contributions to the ratio are presented in table 13–48. Higher values for C_3A/SO_3 and possibly air content, C_4AF, and P were associated with higher ratios. Higher values for C_3A, C_3S, K_2O, and possibly loss-on-ignition, MgO, and Li were associated with lower ratios. Variations of C_3A, C_3A/SO_3 and C_3S had the greatest effect on the calculated range of contributions to AE98/70.

6.7. Effect of 24-Hour Water Storage of Air-Dried Concrete on Dynamic Modulus

6.7.1. Ratio of 71-Day (24-Hour Water Storage) to 70-Day (Air-Dried) Dynamic Modulus of Series O Concretes

The frequency distribution of the ratio of dynamic modulus after one day of soaking to that of air-dried Series O concretes (OE98/70) is presented in table 13–49. The concretes made with more than half of the cements decreased slightly in dynamic modulus when the air-dried specimens were placed in water for 24 hours. Other specimens showed a slight increase in dynamic modulus. As indicated in tables 13–41 and 13–45, storage in

TABLE 13–39. *Coefficients for equations relating AE 70/14, the ratio of dynamic Youn curing) of Series A concretes made with NA*

Eq. No.	Note	Const.	Air content	C_3A	C_4AF	CaO	Al_2O_3	Fe_2O_3
1	1	AE 70/14 = +0.930 s.d. = (0.027)	−0.00802 (0.00289)	−0.00809 (0.00104)	−0.00198 (0.00132)			
2	1	AE 70/14 = +0.928 s.d. = (0.027)	−0.00708 (0.00291)	−0.00794 (0.00106)	−0.00234 (0.00134)			
2A	2	AE 70/14 (odd) = +0.946 s.d. = (0.045)	−0.00772 (0.00491)	−0.00977 (0.00179)	−0.00414 (0.00233)			
2B	2	AE 70/14 (even) = +0.917 s.d. = (0.038)	−0.00637 (0.00406)	−0.00656 (0.00143)	*−0.00122 (0.00179)			
3	1	AE 70/14 = +1.233 s.d. = (0.168)	−0.00817 (0.00291)			−0.00437 (0.00246)	−0.0217 (0.0028)	+0.00429 (0.00375)
4	1	AE 70/14 = +0.932 s.d. = (0.027)	−0.00815 (0.00288)				−0.0199 (0.0029)	+0.00491 (0.00339)
4A	2	AE 70/14 (odd) = +0.958 s.d. = (0.044)	−0.00986 (0.00468)				−0.0260 (0.0048)	*+0.00298 (0.00589)
4B	2	AE 70/14 (even) = +0.917 s.d. = (0.037)	−0.00674 (0.00393)				−0.0158 (0.0038)	+0.00565 (0.00457)

Note 1, 160 cements, Avg. = 0.9293, S.D. = 0.04321
Note 2, 80 cements
*Coef./s.d. ratio less than one.

TABLE 13–40. *Calculated contributions of independent variables to AE70/14, the ratio of dynamic modulus of Series A concretes after drying in air for 8 weeks divided by the dynamic modulus after the original 14 days moist curing*

Independent variable	Range of variables (percent)	Coefficients from eq 2 table 13–39	Calculated contributions to AE70/14	Calculated range of contributions to AE70/14
			Const. = +0.928	
Air-content, NAE cements	0 to 4.5	−0.00708	0 to −0.032	0.032
C_3A	1 to 15	−0.00794	−0.008 to −0.119	0.111
C_4AF**	1 to 17	−0.00234	−0.002 to −0.040	0.038
SO_3	1.2 to 3.0	+0.0732	+0.088 to +0.220	0.132
Na_2O	0 to 0.7	−0.0432	0 to −0.030	0.030
MgO**	0 to 5.0	+0.0038	0 to +0.019	0.019
APF	*2500 to 5500	−0.0000169	−0.042 to −0.093	0.051
Loss	0.3 to 3.3	+0.0161	+0.005 to +0.053	0.048
Co**	0 to 0.01	+2.53	0 to +0.025	0.025
Rb**	0 to 0.01	−1.45	0 to −0.014	0.014
Mn**	0 to 1.0	+0.0392	0 to +0.039	0.039

*cm^2/g.
**Coefficient of doubtful significance as coef./s.d. ratio was less than 2.0.

water for 28 days resulted in an increase of the dynamic modulus with all the concretes.

The inclusion of C_3A, C_3S, K_2O, C_3A/SO_3, Loss, and MgO as independent variables in eq 1 of table 13–50 resulted in a significant reduction of the S.D. value. The use of Co, Ni, Zr, and Mn together with commonly determined variables in eq 2 caused an additional reduction in variance. (See also table 13–57.) The use of SiO_2 and Al_2O_3/SO_3 in eqs 3 and 4 in place of C_3A and C_3S, MgO and C_3A/SO_3 resulted in similar S.D. values.

In equations calculated for the "odds" and "evens" in the array of cements, the coef./s.d. ratio for C_3S, K_2O, MgO, Co, Ni, and Mn was less than 1.0 in one or the other of the equations for the smaller lots of cements.

A corresponding series of equations calculated for the NAE cements is presented in table 13–51. The independent variables, their coefficients and coef./s.d. ratios were generally in agreement with

g's modulus of elasticity at 70 days (after drying in air) to that at 14 days (after moist E cements, to various independent variables

SO_3	Na_2O	MgO	APF	Loss	Co	Li	Rb	Mn	S.D.
+0.0718 (0.0090)	−0.0451 (0.0148)	+0.0045 (0.0021)	−0.0000166 (0.0000058)	+0.0168 (0.0051)					0.03088
+0.0732 (0.0089)	−0.0432 (0.0147)	+0.0038 (0.0021)	−0.0000169 (0.0000059)	+0.0161 (0.0051)	+2.53 (1.74)		−1.45 (1.33)	+0.0392 (0.0208)	0.03049
+0.0761 (0.0138)	−0.0334 (0.0269)	+0.0041 (0.0034)	−0.0000156 (0.0000105)	+0.0179 (0.0090)	+3.15 (2.32)		*−1.21 (2.06)	+0.0483 (0.0283)	0.03212
+0.0686 (0.0140)	−0.0456 (0.0194)	+0.0032 (0.0032)	−0.0000170 (0.0000070)	+0.0148 (0.0070)	*+1.23 (3.10)		*−1.29 (2.07)	*+0.0333 (0.0360)	0.03077
+0.0695 (0.0093)	−0.0492 (0.0150)		−0.0000147 (0.0000060)	+0.0138 (0.0053)					0.03100
+0.0731 (0.0088)	−0.0542 (0.0160)		−0.0000154 (0.0000058)	+0.0142 (0.0051)	+2.87 (1.75)	+1.45 (0.79)		+0.0474 (0.0203)	0.03043
+0.0792 (0.0136)	−0.0341 (0.0288)		−0.0000160 (0.0000104)	+0.0157 (0.0096)	+2.77 (2.29)	*+0.85 (1.26)		+0.0544 (0.0275)	0.03209
+0.0673 (0.0136)	−0.0588 (0.0205)		−0.0000150 (0.0000074)	+0.0138 (0.0068)	*+2.63 (3.07)	+1.65 (1.07)		+0.0456 (0.0344)	0.03036

Table 13–41. *Frequency distribution of cements with respect to OE 98/70, the ratio of dynamic modulus of Series O concretes determined after 4 weeks in water divided by the values after the previous 8 weeks in laboratory air*

Type cement	Dynamic *E* ratio									
	1.00 to 1.05	1.05 to 1.10	1.10 to 1.15	1.15 to 1.20	1.20 to 1.25	1.25 to 1.30	1.30 to 1.35	1.35 to 1.40	1.40 to 1.45	Total
	Number of cements									
I		17	40	16	8	1				82
IA			3	2	2	1				8
II		9	19	22	13	3	2			68
IIA			2			1				3
III	8	5	6	1						20
IIIA		3								3
IV, V		1	4	5	2		2		1	15
Total	8	35	74	46	25	6	4	0	1	199

TABLE 13–42. *Coefficients for equations relating OE 98/70, the ratio of dynamic You days (after drying in air) of Series O concretes made wit*

Eq. No.	Note	Const.	Air content	C_3A	C_3S	C_4AF	CaO	SiO_2
1	1	OE 98/70 = +1.359	+0.00997	−0.0173	−0.00395	+0.00245	------	------
		s.d. = (0.043)	(0.00195)	(0.0025)	(0.00054)	(0.00190)	------	------
2	1	OE 98/70 = +1.374	+0.01010	−0.0178	−0.00411	+0.00261	------	------
		s.d. = (0.042)	(0.00189)	(0.0024)	(0.00053)	(0.00186)	------	------
2A	2	OE 98/70 (odd) = +1.362	+0.01080	−0.0163	−0.00349	* +0.00067	------	------
		s.d. = (0.054)	(0.00260)	(0.0039)	(0.00070)	(0.00280)	------	------
2B	3	OE 98/70 (even) = +1.432	+0.01026	−0.0197	−0.00518	* +0.00267	------	------
		s.d. = (0.070)	(0.00273)	(0.0031)	(0.00083)	(0.00268)	------	------
3	1	OE 98/70 = +1.799	+0.00925	------	------	------	−0.0206	+0.0269
		s.d. = (0.326)	(0.00191)	------	------	------	(0.0044)	(0.0036)
4	1	OE 98/70 = +1.922	+0.00920	------	------	------	−0.0227	+0.0280
		s.d. = (0.321)	(0.00187)	------	------	------	(0.0044)	(0.0036)
4A	2	OE 98/70 (odd) = +1.676	+0.00989	------	------	------	−0.0177	+0.0251
		s.d. = (0.512)	(0.00257)	------	------	------	(0.0068)	(0.0053)
4B	3	OE 98/70 (even) = +2.032	+0.00974	------	------	------	−0.0268	+0.0340
		s.d. = (0.406)	(0.00266)	------	------	------	(0.0058)	(0.0049)

Note 1, 179 cements, Avg. = 1.152, S.D. = 0.06653 Note 2, 90 cements Note 3, 89 cements
*Coef./s.d. ratio less than one.

TABLE 13–43. *Coefficients for equations relating OE 98/70, the ratio of dynamic You days (after drying in air) of Series O concretes made*

Eq. No.	Note	Const.	Air content	C_3A	C_3S	C_4AF	CaO	SiO_2
1	1	OE 98/70 = +1.351	+0.0144	−0.0172	−0.00403	+0.00261	------	------
		s.d. = (0.045)	(0.0049)	(0.0026)	(0.00056)	(0.00196)	------	------
2	1	OE 98/70 = +1.366	+0.0170	−0.0179	−0.00423	+0.00278	------	------
		s.d. = (0.044)	(0.0050)	(0.0025)	(0.00055)	(0.00190)	------	------
2A	2	OE 98/70 (odd) = +1.285	+0.0243	−0.0157	−0.00336	+0.00649	------	------
		s.d. = (0.054)	(0.0066)	(0.0040)	(0.00067)	(0.00251)	------	------
2B	3	OE 98/70 (even) = +1.506	+0.0094	−0.0192	−0.00582	* −0.00163	------	------
		s.d. = (0.078)	(0.0079)	(0.0034)	(0.00095)	(0.00311)	------	------
3	1	OE 98/70 = +1.878	+0.0123	------	------	------	−0.0219	+0.0266
		s.d. = (0.336)	(0.0048)	------	------	------	(0.0046)	(0.0037)
4	1	OE 98/70 = +2.006	+0.0145	------	------	------	−0.0242	+0.0282
		s.d. = (0.330)	(0.0049)	------	------	------	(0.0045)	(0.0037)
4A	2	OE 98/70 (odd) = +2.463	+0.0185	------	------	------	−0.0279	+0.0204
		s.d. = (0.484)	(0.0066)	------	------	------	(0.0062)	(0.0054)
4B	3	OE 98/70 (even) = +1.904	+0.0095	------	------	------	−0.0253	+0.0353
		s.d. = (0.477)	(0.0079)	------	------	------	(0.0068)	(0.0055)

Note 1, 167 cements, Avg. = 1.151, S.D. = 0.06643 Note 2, 84 cements Note 3, 83 cements
*Coef./s.d. ratio less than one.

TABLE 13–44. *Calculated contributions of independent variables to OE 98/70, the ratio of the dynamic modulus of Series O concretes after 28 days in water divided by the dynamic modulus after the previous 8 weeks in air*

Independent variable	Range of variables (percent)	Coefficients from eq 2 table 13–43	Calculated contributions to OE98/70	Calculated range of contributions to OE98/70
			Const. = +1.366	
Air-content, NAE cements	0 to 4.5	+0.0170	0 to +0.077	0.077
C_3A	1 to 15	−0.0179	−0.018 to −0.268	0.250
C_3S	20 to 65	−0.00423	−0.084 to −0.274	0.190
C_4AF**	1 to 17	+0.00278	+0.003 to +0.047	0.044
K_2O	0 to 1.1	−0.0566	0 to −0.062	0.062
Loss	0.3 to 3.3	−0.0191	−0.006 to −0.063	0.057
MgO	0 to 5.0	−0.0065	0 to −0.032	0.032
C_3A/SO_3	0.4 to 10.1	+0.0340	+0.014 to +0.343	0.329
Co**	0 to 0.01	−3.48	0 to −0.035	0.035
Li	0 to 0.02	−2.97	0 to −0.059	0.059
Zr**	0 to 0.5	+0.149	0 to +0.074	0.074
P**	0 to 0.5	+0.0422	0 to +0.021	0.021

**Coefficient of doubtful significance as coef./s.d. ratio was less than 2.0.

those of the previous table where the AE cements were included.

Using the coefficients of the independent variables of eq 2, table 13–51, calculations were made of the estimated contributions to the OE71/70 dynamic modulus values. These calculated contributions are presented in table 13–52 together with the calculated ranges of these contributions. Increases of air content, C_3A/SO_3, and Zr were associated with increases of the ratio (OE71/70). Increases of C_3A, K_2O, Loss, MgO, and possibly Ni were associated with decreases of the OE71/70 values.

6.7.2. Ratio of 71-Day (24-Hour Water Storage) to 70-Day (Air-Dried) Dynamic Modulus of Series A Concretes

The frequency distribution of the ratio of dynamic modulus after 24 hours soaking to that of

ng's modulus of elasticity at 98 days (after soaking in water for 28 days) to that at 70
h AE ± NAE cements, to various independent variables

K_2O	Loss	MgO	C_3A	$\frac{Al_2O_3}{SO_3}$	Co	Li	Zr	P	S.D.
−0.0427 (0.0178)	−0.0227 (0.0065)	−0.0091 (0.0031)	+0.0351 (0.0043)						0.04420
−0.0495 (0.0178)	−0.0232 (0.0065)	−0.0069 (0.0031)	+0.0339 (0.0042)		−3.13 (2.35)	−2.53 (1.01)	+0.162 (0.084)	+0.0506 (0.0305)	0.04286
−0.0891 (0.0266)	−0.0141 (0.0097)	*−0.0009 (0.0045)	+0.0286 (0.0068)		*−0.69 (3.54)	−3.06 (1.47)	+0.135 (0.090)	+0.1546 (0.0532)	0.04243
*−0.0161 (0.0245)	−0.0316 (0.0092)	−0.0104 (0.0043)	+0.0376 (0.0054)		−4.05 (3.17)	−2.23 (1.40)	+0.329 (0.230)	*+0.0109 (0.0370)	0.04173
−0.0483 (0.0184)	−0.0255 (0.0074)	−0.0137 (0.0043)		+0.0526 (0.0062)					0.04433
−0.0577 (0.0187)	−0.0271 (0.0074)	−0.0127 (0.0043)		+0.0497 (0.0061)	−2.72 (2.35)	−2.51 (1.02)	+0.142 (0.084)	+0.0419 (0.0307)	0.04328
−0.0968 (0.0279)	−0.0157 (0.0116)	*−0.0040 (0.0070)		+0.0385 (0.0096)	*+0.36 (3.46)	−3.22 (1.48)	+0.128 (0.091)	+0.1458 (0.0535)	0.04284
*−0.0220 (0.0251)	−0.0362 (0.0099)	−0.0171 (0.0054)		+0.0584 (0.0077)	−4.56 (3.14)	−2.03 (1.39)	+0.262 (0.227)	*+0.0031 (0.0366)	0.04152

ng's modulus of elasticity at 98 days (after soaking in water for 28 days) to that at 70
with NAE cements, to various independent variables

K_2O	Loss	MgO	$\frac{C_3A}{SO_3}$	$\frac{Al_2O_3}{SO_3}$	Co	Li	Zr	P	S.D.
−0.0461 (0.0187)	−0.0192 (0.0068)	−0.0091 (0.0032)	+0.0351 (0.0044)						0.04457
−0.0566 (0.0189)	−0.0191 (0.0067)	−0.0065 (0.0032)	+0.0340 (0.0043)		−3.48 (2.44)	−2.97 (1.05)	+0.149 (0.084)	+0.0422 (0.0312)	0.04305
−0.0894 (0.0260)	−0.0169 (0.0088)	*−0.0028 (0.0046)	+0.0292 (0.0073)		−7.88 (4.78)	−4.35 (1.38)	+0.155 (0.084)	+0.1266 (0.0506)	0.04076
*−0.0276 (0.0281)	−0.0223 (0.0107)	−0.0101 (0.0046)	+0.0354 (0.0057)		*−2.69 (3.05)	−2.46 (1.63)	*−0.265 (0.863)	*+0.0093 (0.0414)	0.04391
−0.0524 (0.0193)	−0.0223 (0.0076)	−0.0145 (0.0045)		+0.0532 (0.0063)					0.04456
−0.0657 (0.0198)	−0.0233 (0.0076)	−0.0132 (0.0044)		+0.0505 (0.0062)	−3.08 (2.43)	−2.88 (1.06)	+0.124 (0.085)	+0.0361 (0.0314)	0.04336
−0.1127 (0.0284)	−0.0278 (0.0108)	−0.0150 (0.0066)		+0.0411 (0.0104)	*−4.33 (4.73)	−3.96 (1.43)	+0.124 (0.087)	+0.1172 (0.0524)	0.04219
*−0.0257 (0.0292)	−0.0244 (0.0118)	−0.0141 (0.0064)		+0.0547 (0.0083)	*−3.07 (3.09)	−2.61 (1.66)	*−0.324 (0.872)	*−0.0090 (0.0419)	0.04450

TABLE 13–45. *Frequency distribution of cements with respect to AE 98/70, the ratio of dynamic modulus of Series A concretes determined after 4 weeks in water divided by the values after the previous 8 weeks in laboratory air*

Type cement	Dynamic E ratio									
	1.00 to 1.05	1.05 to 1.10	1.10 to 1.15	1.15 to 1.20	1.20 to 1.25	1.25 to 1.30	1.30 to 1.35	1.35 to 1.40	1.40 to 1.45	Total
	Number of cements									
I		16	34	18	10	1				79
IA		1	3	2	2					8
II		10	21	16	14	4	2			67
IIA			2			1				3
III	8	4	7	1						20
IIIA		2	1							3
IV, V			5	5	2		2		1	15
Total	8	33	73	42	28	6	4	0	1	195

TABLE 13–46. *Coefficients for equations relating AE 98/70, the ratio of dynamic You (after drying in air) of Series A concretes made with*

Eq. No.	Note		Const.	Air content	C_3A	C_3S	C_4AF	CaO	SiO_2
1	1	AE 98/70	= +1.447	+0.00455	+0.00458	−0.00308	+0.00334	----	----
		s.d.	= (0.040)	(0.00158)	(0.00134)	(0.00051)	(0.00177)	----	----
2	1	AE 98/70	= +1.332	+0.00469	−0.01209	−0.00351	+0.00313	----	----
		s.d.	= (0.059)	(0.00155)	(0.00656)	(0.00053)	(0.00174)	----	----
3	1	AE 98/70	= +1.315	+0.00469	−0.01446	−0.00358	+0.00308	----	----
		s.d.	= (0.040)	(0.00155)	(0.00228)	(0.00050)	(0.00173)	----	----
4	1	AE 98/70	= +1.333	+0.00491	−0.01555	−0.00376	+0.00325	----	----
		s.d.	= (0.039)	(0.00151)	(0.00224)	(0.00049)	(0.00169)	----	----
4A	2	AE 98/70 (odd)	= +1.299	+0.00566	−0.01831	−0.00299	+0.00322	----	----
		s.d.	= (0.056)	(0.00193)	(0.00356)	(0.00070)	(0.00252)	----	----
4B	2	AE 98/70 (even)	= +1.390	+0.00424	−0.01550	−0.00471	*+0.00229	----	----
		s.d.	= (0.056)	(0.00256)	(0.00294)	(0.00072)	(0.00237)	----	----
5	1	AE 98/70	= +1.795	+0.00446	----	----	----	−0.0187	+0.0212
		s.d.	= (0.291)	(0.00152)	----	----	----	(0.0040)	(0.0032)
6	1	AE 98/70	= +1.918	+0.00452	----	----	----	−0.0211	+0.0230
		s.d.	= (0.285)	(0.00148)	----	----	----	(0.0039)	(0.0032)
6A	2	AE 98/70 (odd)	= +1.595	+0.00499	----	----	----	−0.0163	+0.0233
		s.d.	= (0.468)	(0.00192)	----	----	----	(0.0062)	(0.0050)
6B	2	AE 98/70 (even)	= +2.022	+0.00427	----	----	----	−0.0238	+0.0258
		s.d.	= (0.368)	(0.00251)	----	----	----	(0.0052)	(0.0043)

Note 1, 172 cements, Avg. = 1.148, S.D. = 0.06000
Note 2, 86 cements
*Coef./s.d. ratio less than 1.

TABLE 13–47. *Coefficients for equations relating AE 98/70, the ratio of dynamic You (after drying in air) of Series A concretes made*

Eq. No.	Note		Const.	Air content	C_3A	C_3S	C_4AF	CaO	SiO_2
1	1	AE 98/70	= +1.435	+0.00674	+0.00493	−0.00309	+0.00375	----	----
		s.d.	= (0.042)	(0.00385)	(0.00138)	(0.00053)	(0.00180)	----	----
2	1	AE 98/70	= +1.332	+0.00698	−0.01019	−0.00346	+0.00352	----	----
		s.d.	= (0.061)	(0.00380)	(0.00673)	(0.00055)	(0.00178)	----	----
3	1	AE 98/70	= +1.304	+0.00700	−0.01411	−0.00357	+0.00343	----	----
		s.d.	= (0.041)	(0.00380)	(0.00237)	(0.00052)	(0.00177)	----	----
4	1	AE 98/70	= +1.322	+0.00854	−0.01528	−0.00376	+0.00358	----	----
		s.d.	= (0.040)	(0.00386)	(0.00232)	(0.00051)	(0.00173)	----	----
4A	2	AE 98/70 (odd)	= +1.282	*+0.00532	−0.01652	−0.00367	+0.00597	----	----
		s.d.	= (0.059)	(0.00657)	(0.00364)	(0.00072)	(0.00288)	----	----
4B	3	AE 98/70 (even)	= +1.355	+0.01100	−0.01431	−0.00408	+0.00244	----	----
		s.d.	= (0.058)	(0.00495)	(0.00317)	(0.00076)	(0.00225)	----	----
5	1	AE 98/70	= +1.891	+0.00609	----	----	----	−0.0199	+0.0202
		s.d.	= (0.297)	(0.00373)	----	----	----	(0.0040)	(0.0033)
6	1	AE 98/70	= +2.010	+0.00751	----	----	----	−0.0223	+0.0222
		s.d.	= (0.290)	(0.00379)	----	----	----	(0.0040)	(0.0033)
6A	2	AE 98/70 (odd)	= +2.103	*+0.00297	----	----	----	−0.0237	+0.0219
		s.d.	= (0.483)	(0.00654)	----	----	----	(0.0064)	(0.0053)
6B	3	AE 98/70 (even)	= +1.964	+0.01103	----	----	----	−0.0219	+0.0231
		s.d.	= (0.366)	(0.00479)	----	----	----	(0.0051)	(0.0043)

Note 1, 161 cements, Avg. = 1.148, S.D. = 0.05965
Note 2, 81 cements
Note 3, 80 cements
*Coef./s.d. ratio less than 1.

ng's modulus of elasticity at 98 days (after 28 days soaking in water) to that at 70 days AE + NAE cements, to various independent variables

SO_3	K_2O	Loss	$\frac{C_3A}{SO_3}$	$\frac{Al_2O_3}{SO_3}$	MgO	Li	P	Co	S.D.
−0.0856 (0.0106)	−0.0519 (0.0168)	−0.0158 (0.0062)			−0.00929 (0.00290)				0.04053
*−0.0117 (0.0303)	−0.0527 (0.0165)	−0.0181 (0.0062)	+0.0313 (0.0120)		−0.00858 (0.00286)				0.03983
	−0.0532 (0.0164)	−0.0187 (0.0060)	+0.0357 (0.0041)		−0.00850 (0.00285)				0.03973
	−0.0632 (0.0164)	−0.0172 (0.0059)	+0.0356 (0.0040)		−0.00716 (0.00281)	−2.19 (0.91)	+0.0667 (0.0291)	−3.22 (2.13)	0.03861
	−0.0611 (0.0241)	−0.0160 (0.0087)	+0.0384 (0.0062)		−0.00448 (0.00409)	−2.74 (1.47)	+0.1949 (0.0591)	−6.43 (3.31)	0.03887
	−0.0590 (0.0241)	−0.0181 (0.0087)	+0.0372 (0.0054)		−0.01158 (0.00428)	−1.62 (1.22)	*+0.0317 (0.0341)	*+0.22 (2.95)	0.03792
	−0.0565 (0.0168)	−0.0217 (0.0068)		+0.0566 (0.0058)	−0.01314 (0.00394)				0.03965
	−0.0698 (0.0169)	−0.0215 (0.0067)		+0.0551 (0.0056)	−0.01288 (0.00384)	−2.28 (0.91)	+0.0605 (0.0289)	−3.28 (2.10)	0.03853
	−0.0754 (0.0242)	−0.0157 (0.0107)		+0.0547 (0.0088)	−0.00729 (0.00648)	−2.92 (1.49)	+0.1741 (0.0597)	−5.15 (3.23)	0.03936
	−0.0651 (0.0251)	−0.0225 (0.0093)		+0.0600 (0.0076)	−0.01699 (0.00517)	−1.74 (1.20)	*+0.0322 (0.0337)	*−0.31 (2.94)	0.03786

ng's modulus of elasticity at 98 days (after 28 days soaking in water) to that at 70 days with NAE cements, to various independent variables

SO_3	K_2O	Loss	$\frac{C_3A}{SO_3}$	$\frac{Al_2O_3}{SO_3}$	MgO	Li	P	Co	S.D.
−0.0857 (0.0107)	−0.0533 (0.0175)	−0.0127 (0.0064)			−0.00939 (0.00296)				0.04050
*−0.0192 (0.0309)	−0.0535 (0.0173)	−0.0151 (0.0064)	+0.0282 (0.0123)		−0.00876 (0.00294)				0.03995
	−0.0543 (0.0172)	−0.0162 (0.0062)	+0.0354 (0.0042)		−0.00863 (0.00292)				0.03986
	−0.0665 (0.0174)	−0.0142 (0.0061)	+0.0354 (0.0041)		−0.00699 (0.00290)	−2.46 (0.95)	+0.0604 (0.0295)	−3.39 (2.20)	0.03864
	−0.0536 (0.0270)	−0.0190 (0.0111)	+0.0394 (0.0064)		*−0.00420 (0.00440)	−2.21 (1.60)	+0.1687 (0.0504)	*1.92 (2.87)	0.04000
	−0.0760 (0.0242)	−0.0137 (0.0078)	+0.0339 (0.0056)		−0.00870 (0.00421)	−2.93 (1.28)	*−0.0046 (0.0380)	−6.89 (3.76)	0.03704
	−0.0589 (0.0175)	−0.0200 (0.0070)		+0.0564 (0.0059)	−0.01428 (0.00405)				0.03962
	−0.0745 (0.0177)	−0.0191 (0.0068)		+0.0551 (0.0057)	−0.01371 (0.00394)	−2.52 (0.94)	+0.0552 (0.0292)	−3.48 (2.16)	0.03837
	−0.0703 (0.0277)	−0.0226 (0.0131)		+0.0591 (0.0091)	−0.01249 (0.00649)	−2.33 (1.60)	+0.1667 (0.0510)	*−1.43 (2.83)	0.04038
	−0.0802 (0.0243)	−0.0180 (0.0082)		+0.0570 (0.0078)	−0.01427 (0.00511)	−3.09 (1.23)	*−0.0106 (0.0363)	−7.92 (3.64)	0.03593

TABLE 13–48. *Calculated contributions of independent variables to AE 98/70, the ratio of the dynamic modulus of Series A concretes after 28 days in water divided by the dynamic modulus after the previous 8 weeks in air*

Independent variable	Range of variables (percent)	Coefficients from eq 4 table 13–47	Calculated contributions to AE98/70	Calculated range of contributions to AE98/70
			Const. = +1.322	
Air-content, NAE cements	0 to 4.5	+0.00854	0 to +0.038	0.038
C_3A	1 to 15	−0.01528	−0.015 to −0.229	0.214
C_3S	20 to 65	−0.00376	−0.075 to −0.244	0.169
C_4AF	1 to 17	+0.00358	+0.004 to +0.061	0.057
K_2O	0 to 1.1	−0.0665	0 to −0.073	0.073
Loss	0.3 to 3.3	−0.0142	−0.004 to −0.047	0.043
C_3A/SO_3	0.4 to 10.1	+0.0354	+0.014 to +0.358	0.344
MgO	0 to 5.0	−0.00699	−0.007 to −0.035	0.028
Li	0 to 0.02	−2.46	0 to −0.049	0.049
P	0 to 0.5	+0.0604	0 to +0.030	0.030
Co**	0 to 0.01	−3.39	0 to −0.033	0.033

**Coefficient of doubtful significance as coef./s.d. ratio was less than 2.0.

TABLE 13–49. *Frequency distribution of cements with respect to OE 71/70, the ratio of dynamic modulus of Series O concretes determined after 24 hours in water divided by the values after the previous 8 weeks in laboratory air*

Type cement	Dynamic E ratio								Total
	0.92 to 0.94	0.94 to 0.96	0.96 to 0.98	0.98 to 1.00	1.00 to 1.02	1.02 to 1.04	1.04 to 1.06	1.06 to 1.08	
	Number of cements								
I	1	7	18	24	16	10	-----	-----	76
IA	-----	-----	1	3	2	1	-----	1	8
II	-----	2	18	17	19	3	5	-----	64
IIA	-----	-----	-----	-----	1	2	-----	-----	3
III	-----	4	7	7	2	-----	-----	-----	20
IIIA	-----	-----	1	2	-----	-----	-----	-----	3
IV, V	-----	1	1	4	4	1	2	-----	13
Total	1	14	46	57	44	17	7	1	187

air-dried Series A concretes (AE71/70) is presented in table 13–53. As was found for the Series O concretes, the Series A concretes made with most of the cements showed a slight reduction of dynamic modulus when the air-dried specimens were placed in water for 24 hours. There was an overlapping of the values for the concretes made with the different types of cement.

Equations are presented in table 13–54 indicating the independent variables associated with the AE71/70 dynamic-modulus ratio of concretes made with AE + NAE cements. The use of the commonly determined independent variables, air content, C_3A, C_3S, K_2O, C_3A/SO_3 and MgO in eq 1 resulted in a highly significant reduction of the S.D. value. The additional use of the trace elements Zr, Co, Li, Rb, and Ni as independent variables in eq 2 resulted in a further significant reduction of variance. In eq 4 the use of the trace elements Zr, Co, Li, Rb, Ni, and Ti, together with the commonly determined variables, also resulted in a significant reduction of variance. (See table 13–57.)

In eqs 2A, 2B, 4A, and 4B calculated for the "odds" and "evens" in the array of cements the coef./s.d. ratios for C_3S, Loss, MgO, Zr, Rb, Ni, and Ti were less than 1.0 in one or more of the equations for the smaller lots of cement.

A corresponding series of equations for the NAE cements is presented in table 13–55. The independent variables, their coefficients, and coef./s.d. ratios were generally in agreement with those of the previous table where the AE cements were included. The use of commonly determined independent variables or these with the trace elements resulted in a significant reduction of variance.

Using the coefficients of the independent variables of eq 2 table 13–55 and the ranges of these variables, computations were made of the estimated contributions to the AE71/70 dynamic-modulus values. These calculated contributions are presented in table 13–56 together with the calculated ranges of these contributions. Higher values for air content and C_3A/SO_3 were associated with higher ratios (AE71/70).

Higher values for C_3A, K_2O, and possibly Loss, MgO, and Li were associated with lower values for the ratio.

TABLE 13-50. *Coefficients for equations relating OE 71/70, the ratio of dynamic Young's modulus of elasticity at 71 days (after soaking in water for 24 hours) to that at 70 days (after drying in air) of Series O concretes made with AE + NAE cements, to various independent variables*

Eq. No.	Note		Const.	Air content	C_3A	C_3S	SiO_2	K_2O	$\frac{C_3A}{SO_3}$	$\frac{Al_2O_3}{SO_3}$	Loss	MgO	Co	Ni	Zr	Mn	S.D.
1	1	OE 71/70	= +1.038	+0.00456	−0.00446	−0.000397		−0.0224	+0.00819		−0.0148	−0.00285					0.01967
		s.d.	= (0.013)	(0.00086)	(0.00107)	(0.000238)		(0.0080)	(0.00193)		(0.0030)	(0.00141)					
2	1	OE 71/70	= +1.046	+0.00435	−0.00412	−0.000413		−0.0213	+0.00702		−0.0165	−0.00215	−2.07	−0.898	+0.130	−0.0199	0.01835
		s.d.	= (0.013)	(0.00081)	(0.00100)	(0.000226)		(0.0077)	(0.00182)		(0.0028)	(0.00138)	(1.05)	(0.448)	(0.036)	(0.0122)	
2A	2	OE 71/70 (odd)	= +1.027	+0.00510	−0.00377	−0.000154		−0.0194	+0.00645		−0.0168	*−0.00016	+2.35	−0.651	+0.241	−0.0478	0.01789
		s.d.	= (0.017)	(0.00122)	(0.00155)	(0.000286)		(0.0112)	(0.00306)		(0.0038)	(0.00191)	(1.43)	(0.633)	(0.095)	(0.0208)	
2B	3	OE 71/70 (even)	= +1.072	+0.00331	−0.00453	−0.000830		−0.0140	+0.00768		−0.0160	−0.00541	−2.54	−1.081	+0.109	*+0.0013	0.01892
		s.d.	= (0.022)	(0.00119)	(0.00144)	(0.000392)		(0.0118)	(0.00243)		(0.0047)	(0.00219)	(1.63)	(0.698)	(0.041)	(0.0163)	
3	1	OE 71/70	= +0.817	+0.00428			+0.00737	−0.0206		+0.0107	−0.0115						0.01941
		s.d.	= (0.039)	(0.00084)			(0.00147)	(0.0077)		(0.0027)	(0.0031)						
4	1	OE 71/70	= +0.847	+0.00408			+0.00655	−0.0195		+0.0087	−0.0139		−1.83	−0.812	+0.131	−0.0177	0.01821
		s.d.	= (0.037)	(0.00079)			(0.00140)	(0.0074)		(0.0026)	(0.0030)		(1.04)	(0.437)	(0.035)	(0.0116)	
4A	2	OE 71/70 (odd)	= +0.897	+0.00480			+0.00448	−0.0204		+0.0072	−0.0153		−2.10	*−0.556	+0.232	−0.0465	0.01771
		s.d.	= (0.051)	(0.00113)			(0.00191)	(0.0098)		(0.0042)	(0.0040)		(1.40)	(0.610)	(0.093)	(0.0201)	
4B	3	OE 71/70 (even)	= +0.774	+0.00305			+0.00938	*−0.0093		+0.0102	−0.0115		*−1.53	−0.850	+0.119	*−0.0028	0.01888
		s.d.	= (0.058)	(0.00119)			(0.00220)	(0.0120)		(0.0034)	(0.0048)		(1.60)	(0.671)	(0.040)	(0.0155)	

Note 1, 169 cements, Avg. = 0.9922, S.D. = 0.02501
Note 2, 85 cements
Note 3, 84 cements
*Coef./s.d. ratio less than one.

TABLE 13-51. *Coefficients for equations relating OE 71/70, the ratio of dynamic Young's modulus of elasticity at 71 days (after soaking in water for 24 hours) to that at 70 days (after drying in air) of Series O concretes made of NAE cements, to various independent variables*

Eq. No.	Note		Const.	Air content	C_3A	C_3S	SiO_2	K_2O	$\frac{C_3A}{SO_3}$	$\frac{Al_2O_3}{SO_3}$	Loss	MgO	Co	Ni	Zr	Mn	S.D.
1	1	OE 71/70	= +1.037	+0.00600	−0.00427	−0.000395		−0.0212	+0.00768		−0.0142	−0.00335					0.01981
		s.d.	= (0.014)	(0.00224)	(0.00111)	(0.000249)		(0.0085)	(0.00198)		(0.0031)	(0.00146)					
2	1	OE 71/70	= +1.045	+0.00634	−0.00395	−0.000420		−0.0200	+0.00646		−0.0156	−0.00284	−1.63	−1.12	+0.128	−0.0152	0.01844
		s.d.	= (0.013)	(0.00211)	(0.00104)	(0.000236)		(0.0082)	(0.00187)		(0.0030)	(0.00142)	(1.10)	(0.46)	(0.036)	(0.0128)	
2A	2	OE 71/70 (odd)	= +1.024	+0.00526	−0.00235	*−0.000166		−0.0189	+0.00403		−0.0166	*−0.00135	−1.61	*−0.61	*+0.259	−0.0239	0.01954
		s.d.	= (0.021)	(0.00371)	(0.00175)	(0.000332)		(0.0130)	(0.00338)		(0.0047)	(0.00210)	(1.43)	(0.80)	(0.296)	(0.0207)	
2B	3	OE 71/70 (even)	= +1.068	+0.00736	−0.00511	−0.000745		−0.0227	+0.00782		−0.0134	−0.00392	*−1.77	−1.55	+1.040	*−0.0110	0.01785
		s.d.	= (0.019)	(0.00270)	(0.00141)	(0.000375)		(0.0109)	(0.00237)		(0.0044)	(0.00224)	(2.16)	(0.59)	(0.038)	(0.0174)	
3	1	OE 71/70	= +0.821	+0.00555			+0.00709	−0.0209		+0.0104	−0.0109						0.01965
		s.d.	= (0.040)	(0.00220)			(0.00153)	(0.0081)		(0.0028)	(0.0032)						
4	1	OE 71/70	= +0.848	+0.00570			+0.00637	−0.0198		+0.0085	−0.0130		−1.43	−0.97	+0.131	−0.0152	0.01841
		s.d.	= (0.039)	(0.00208)			(0.00146)	(0.0078)		(0.0026)	(0.0031)		(1.09)	(0.45)	(0.036)	(0.0123)	
4A	2	OE 71/70 (odd)	= +0.909	+0.00436			+0.00405	−0.0176		*+0.0043	−0.0146		−1.59	*−0.62	+0.346	−0.0228	0.01910
		s.d.	= (0.056)	(0.00357)			(0.00208)	(0.0144)		(0.0045)	(0.0048)		(1.38)	(0.78)	(0.287)	(0.0198)	
4B	3	OE 71/70 (even)	= +0.788	+0.00624			+0.00883	−0.0207		+0.0105	−0.0104		*−1.35	−1.25	+0.108	*−0.0091	0.01808
		s.d.	= (0.057)	(0.00265)			(0.00215)	(0.0110)		(0.0034)	(0.0044)		(2.19)	(0.57)	(0.038)	(0.0164)	

Note 1, 157 cements, Avg. = 0.9911, S.D. = 0.02460
Note 2, 79 cements
Note 3, 78 cements
*Coef./s.d. ratio less than one.

TABLE 13–52. *Calculated contributions of independent variables to OE 71/70, the ratio of dynamic modulus of Series O concretes after 24 hours in water divided by the dynamic modulus after the previous 8 weeks in air*

Independent variable	Range of variables (percent)	Coefficients from eq 2 table 13–51	Calculated contributions to OE71/70	Calculated range of contributions to OE71/70
			Const. = +1.045	
Air-content, NAE cements	0 to 4.5	+0.00634	0 to +0.029	0.029
C_3A	1 to 15	−0.00395	−0.004 to −0.059	0.055
C_3S**	20 to 65	−0.00042	−0.008 to −0.027	0.019
K_2O	0 to 1.1	−0.020	0 to −0.022	0.022
C_3A/SO_3	0.4 to 10.1	+0.00646	+0.003 to +0.065	0.062
Loss	0.3 to 3.3	−0.0156	−0.005 to −0.051	0.046
MgO	0 to 5.0	−0.00284	0 to −0.014	0.014
Co**	0 to 0.01	−1.63	0 to −0.016	0.016
Ni	0 to 0.02	−1.12	0 to −0.022	0.022
Zr	0 to 0.5	+0.128	0 to +0.064	0.064
Mn**	0 to 1.0	−0.0152	0 to −0.015	0.015

**Coefficient of doubtful significance as coef./s.d. ratio was less than 2.0.

TABLE 13–53. *Frequency distribution of cements with respect to AE71/70, the ratio of dynamic modulus of Series A concretes determined after 24 hours in water divided by the values after the previous 8 weeks in laboratory air*

Type cement	Dynamic *E* ratio 0.94 to 0.96	0.96 to 0.98	0.98 to 1.00	1.00 to 1.02	1.02 to 1.04	1.04 to 1.06	Total
	Number of cements						
I	6	23	24	12	9	------	74
IA	------	------	2	4	2	------	8
II	2	18	15	19	5	4	63
IIA	------	------	1	1	1	------	3
III	3	9	5	3	------	------	20
IIIA	------	------	2	1	------	------	3
IV, V	------	1	5	4	1	2	13
Total	11	51	54	44	18	6	184

TABLE 13–54. *Coefficients for equations relating AE 71/70, the ratio of dynamic Yo days (after drying in air) of Series A concretes made*

Eq. No.	Note		Const.	Air content	C_3A	C_3S	SiO_2	K_2O	Loss
1	1	AE 71/70 s.d.	= +1.030 = (0.012)	+0.00379 (0.00071)	−0.00428 (0.00103)	−0.000394 (0.000223)	------------ ------------	−0.0205 (0.0077)	−0.00906 (0.00281)
2	1	AE 71/70 s.d.	= +1.038 = (0.012)	+0.00399 (0.00068)	−0.00454 (0.00099)	−0.000382 (0.000216)	------------ ------------	−0.0295 (0.0086)	−0.00882 (0.00279)
2A	2	AE 71/70 (odd) s.d.	= +1.038 = (0.018)	+0.00377 (0.00116)	−0.00296 (0.00155)	−0.000446 (0.000280)	------------ ------------	−0.0245 (0.0118)	−0.01102 (0.00382)
2B	3	AE 71/70 (even) s.d.	= +1.035 = (0.020)	+0.00434 (0.00097)	−0.00537 (0.00141)	*−0.000263 (0.000385)	------------ ------------	−0.0370 (0.0148)	−0.00656 (0.00467)
3	1	AE 71/70 s.d.	= +0.841 = (0.039)	+0.00364 (0.00070)	------------ ------------	------------ ------------	+0.00612 (0.00145)	−0.0185 (0.0076)	−0.00652 (0.00299)
4	1	AE 71/70 s.d.	= +0.842 = (0.038)	+0.00393 (0.00068)	------------ ------------	------------ ------------	+0.00657 (0.00141)	−0.0288 (0.0085)	−0.00682 (0.00299)
4A	2	AE 71/70 (odd) s.d.	= +0.882 = (0.052)	+0.00370 (0.00115)	------------ ------------	------------ ------------	+0.00485 (0.00189)	−0.0256 (0.0113)	−0.00994 (0.00411)
4B	3	AE 71/70 (even) s.d.	= +0.797 = (0.060)	+0.00422 (0.00096)	------------ ------------	------------ ------------	+0.00833 (0.00228)	−0.0307 (0.0149)	*−0.00243 (0.00492)

Note 1, 163 cements, Avg. = 0.9909, S.D. = 0.02300 Note 2, 82 cements Note 3, 81 cements

*Coef./s.d. ratio less than one.

TABLE 13–55. *Coefficients for equations relating AE 71/70, the ratio of dynamic Youn days (after drying in air) of Series A concretes made*

Eq. No.	Note		Const.	Air content	C_3A	C_3S	SiO_2	K_2O	Loss
1	1	AE 71/70 s.d.	= +1.026 = (0.013)	+0.00513 (0.00180)	−0.00435 (0.00109)	−0.000352 (0.000237)	------------ ------------	−0.0206 (0.0083)	−0.00856 (0.00298)
2	1	AE 71/70 s.d.	= +1.035 = (0.013)	+0.00635 (0.00177)	−0.00468 (0.00104)	−0.000358 (0.000227)	------------ ------------	−0.0305 (0.0091)	−0.00790 (0.00294)
2A	2	AE 71/70 (odd) s.d.	= +1.044 = (0.019)	+0.00761 (0.00284)	−0.00558 (0.00176)	−0.000451 (0.000339)	------------ ------------	−0.0277 (0.0137)	−0.01046 (0.00474)
2B	2	AE 71/70 (even) s.d.	= +1.027 = (0.021)	+0.00589 (0.00260)	−0.00433 (0.00146)	*−0.000341 (0.000354)	------------ ------------	−0.0372 (0.0139)	−0.00459 (0.00427)
3	1	AE 71/70 s.d.	= +0.844 = (0.041)	+0.00481 (0.00179)	------------ ------------	------------ ------------	+0.00592 (0.00153)	−0.0195 (0.0081)	−0.00604 (0.00316)
4	1	AE 71/70 s.d.	= +0.841 = (0.040)	+0.00646 (0.00180)	------------ ------------	------------ ------------	+0.00649 (0.00148)	−0.0311 (0.0090)	−0.00599 (0.00314)
4A	2	AE 71/70 (odd) s.d.	= +0.822 = (0.062)	+0.00785 (0.00278)	------------ ------------	------------ ------------	+0.00766 (0.00224)	−0.0317 (0.0130)	−0.01016 (0.00494)
4B	2	AE 71/70 (even) s.d.	= +0.851 = (0.056)	+0.00515 (0.00267)	------------ ------------	------------ ------------	+0.00566 (0.00212)	−0.0353 (0.0140)	*−0.00226 (0.00458)

Note 1, 152 cements, Avg. = 0.9899, S.D. = 0.2291 Note 1, 76 cements

*Coef./s.d. ratio less than 1.

TABLE 13–56. *Calculated contributions of independent variables to AE 71/70, the ratio of the dynamic modulus of Series A concretes after 24 hours in water divided by the dynamic modulus after the previous 3 weeks in air*

Independent variable	Range of variables (percent)	Coefficients from eq 2 table 13–55	Calculated contributions to AE71/70	Calculated range of contributions to AE71/70
			Const. = +1.035	
Air-content, NAE cements	0 to 4.5	+0.00635	0 to +0.029	0.029
C_3A	1 to 15	−0.00468	−0.005 to −0.070	0.065
C_3S**	20 to 65	−0.000358	−0.007 to −0.023	0.016
K_2O	0 to 1.1	−0.0305	0 to −0.034	0.034
Loss	0.3 to 3.3	−0.0079	−0.002 to −0.026	0.024
C_3A/SO_3	0.4 to 10.1	+0.0081	+0.003 to +0.082	0.079
MgO	0 to 5.0	−0.00307	0 to −0.015	0.015
Zr**	0 to 0.5	+0.0567	0 to +0.028	0.028
Co**	0 to 0.01	−1.82	0 to −0.018	0.018
Li	0 to 0.02	−0.912	0 to −0.018	0.018
Rb**	0 to 0.01	+1.68	0 to +0.017	0.017
Ni	0 to 0.02	−1.08	0 to −0.022	0.022

**Coefficient of doubtful significance as coef./s.d. ratio was less than 2.0.

ung's modulus of elasticity at 71 days (after soaking in water for 24 hours) to that at 70 of AE + NAE cements, to various independent variables

$\frac{C_3A}{SO_3}$	$\frac{Al_2O_3}{SO_3}$	MgO	Zr	Co	Li	Rb	Ni	Ti	S.D.
+0.00855 (0.00190)		−0.00388 (0.00135)							0.01837
+0.00811 (0.00182)		−0.00328 (0.00134)	+0.0580 (0.0341)	−1.85 (1.01)	−0.743 (0.430)	+1.84 (0.87)	−0.978 (0.453)		0.01739
+0.00496 (0.00302)		−0.00261 (0.00206)	+0.2239 (0.0887)	−1.81 (1.36)	−0.780 (0.587)	+1.86 (1.08)	−0.813 (0.606)		0.01697
+0.00986 (0.00248)		−0.00382 (0.00206)	*+0.0217 (0.0404)	−1.91 (1.61)	−0.663 (0.662)	*+1.59 (1.60)	−1.144 (0.769)		0.01842
	+0.0114 (0.0027)	−0.00234 (0.00137)							0.01823
	+0.0108 (0.0026)	−0.00191 (0.00137)	+0.0656 (0.0343)	−1.65 (0.99)	−0.813 (0.426)	+1.88 (0.86)	−0.788 (0.455)	−0.0190 (0.0122)	0.01726
	+0.00840 (0.00431)	*−0.00115 (0.00212)	+0.2418 (0.0904)	−1.86 (1.34)	−0.804 (0.588)	+2.09 (1.08)	*−0.527 (0.609)	*−0.0202 (0.0220)	0.01686
	+0.01319 (0.00357)	−0.00237 (0.00207)	*+0.0251 (0.0400)	−1.78 (1.57)	−0.848 (0.662)	*+1.35 (1.56)	−1.137 (0.746)	−0.0250 (0.0160)	0.01814

g's modulus of elasticity at 71 days (after soaking in water for 24 hours) to that at 70 of NAE cements, to various independent variables

$\frac{C_3A}{SO_3}$	$\frac{Al_2O_3}{SO_3}$	MgO	Zr	Co	Li	Rb	Ni	Ti	S.D.
+0.00851 (0.00199)		−0.00382 (0.00142)							0.01881
+0.00810 (0.00189)		−0.00307 (0.00141)	+0.0567 (0.0349)	−1.82 (1.07)	−0.912 (0.455)	+1.68 (0.90)	−1.08 (0.47)		0.01767
+0.00964 (0.00329)		−0.00392 (0.00230)	+0.0542 (0.0405)	−3.77 (2.51)	−1.279 (0.706)	*+0.88 (1.29)	−0.72 (0.70)		0.01898
+0.00779 (0.00263)		−0.00222 (0.00216)	*+0.1258 (0.4165)	*−1.15 (1.26)	−0.757 (0.668)	+2.57 (1.49)	−1.43 (0.74)		0.01751
	+0.0112 (0.0028)	−0.00237 (0.00144)							0.01870
	+0.0108 (0.0027)	−0.00181 (0.00145)	+0.0653 (0.0351)	−1.59 (1.05)	−0.990 (0.453)	+1.72 (0.89)	−0.87 (0.47)	−0.0222 (0.0131)	0.01757
	+0.0121 (0.0045)	−0.00259 (0.00223)	+0.0703 (0.0397)	*−2.39 (2.40)	−1.592 (0.684)	*+0.90 (1.21)	*−0.43 (0.68)	−0.0426 (0.0172)	0.01826
	+0.0098 (0.0038)	*−0.00070 (0.00225)	*+0.1160 (0.4206)	*−1.10 (1.27)	−0.685 (0.666)	+2.55 (1.51)	−1.46 (0.74)	*−0.0081 (0.0230)	0.01756

TABLE 13–57. *"F" values for significance of reduction of variance due to added variables*

Table	Equation*	"F" ratio	D.F.**	Critical "F" Ratio	
				α = 0.01	α = 0.05
13–2	0,1	62.1	9:171	2.52	1.93
	1,2	4.03	3:168	3.88	2.67
	0,3	55.8	10:170	2.40	1.89
	3,4	4.0	3:167	3.88	2.67
13–3	0,1	26.5	8:160	2.62	2.00
	1,2	2.61	4:156	3.44	2.42
	0,3	23.5	9:159	2.52	1.93
	3,4	2.60	4:155	3.43	2.42
13–6	0,1	25.1	2:171	4.72	3.05
	0,2	9.0	2:171	4.72	3.05
	0,3	17.4	3:170	3.88	2.67
	3,4	35.3	6:164	2.92	2.15
	4,5	3.27	2:162	4.74	3.05
	0,6	32.3	10:163	2.40	1.89
	6,7	2.50	3:160	3.89	2.67
13–7	0,4	20.8	9:153	2.52	1.93
	4,5	2.66	3:150	3.90	2.67
	0,6	18.7	10:152	2.40	1.89
	6,7	2.71	3:149	3.90	2.67
13–10	0,1	60.9	9:170	2.52	1.93
	1,2	3.89	1:169	6.77	3.90
	0,3	63.3	9:170	2.52	1.93
	3,4	3.34	1:169	6.77	3.90
13–11	0,1	32.1	9:158	2.52	1.93
	1,2	3.54	1:157	6.78	3.90
	0,3	33.2	9:158	2.52	1.93
	3,4	3.20	1:157	6.78	3.90
13–14	0,1	12.3	2:171	4.72	3.05
	0,2	4.51	2:171	4.72	3.05
	0,3	8.60	3:170	3.88	2.67
	3,4	27.8	7:163	2.75	2.07
	4,5	2.72	3:160	3.89	2.67
	0,6	29.0	9:164	2.52	1.93
	6,7	3.45	2:162	4.73	3.05
13–15	0,4	18.9	10:152	2.40	1.89
	4,5	2.96	3:149	3.90	2.67
	0,6	21.9	9:153	2.52	1.93
	6,7	3.49	2:151	4.75	3.05
13–18	0,1	63.9	10:169	2.40	1.89
	1,2	1.38	1:168	6.76	3.90
	0,3	69.9	9:170	2.52	1.93
	3,4	1.38	1:169	6.76	3.90
13–19	0,1	37.5	10:157	2.40	1.89
	1,2	1.35	1:156	6.78	3.90
	0,3	40.9	9:158	2.52	1.93
	3,4	1.35	1:157	6.78	3.90
13–22	0,1	14.8	2:171	4.72	3.05
	0,2	6.10	2:171	4.72	3.05
	0,3	10.1	3:170	3.88	2.67
	3,4	43.5	8:162	2.62	2.00
	4,5	2.40	1:161	6.77	3.90
	0,6	35.4	10:163	2.40	1.89
	6,7	2.23	1:162	6.77	3.90
13–23	0,4	24.5	11:151	2.38	1.87
	4,5	3.96	1:150	6.78	3.90
	0,6	26.7	10:152	2.40	1.89
	6,7	3.47	1:151	6.78	3.90
13–26	0,1	91.1	8:171	2.62	2.00
	1,2	6.09	3:168	3.88	2.67
	0,3	80.6	9:170	2.52	1.93
	3,4	6.45	3:167	3.88	2.67
13–27	0,1	21.5	8:159	2.62	2.00
	1,2	6.40	3:156	3.89	2.67
	0,3	19.1	9:158	2.52	1.93
	3,4	7.05	3:155	3.89	2.67
13–30	0,1	74.5	3:170	3.88	2.67
	1,2	12.5	5:165	3.13	2.28
	2,3	4.72	5:160	3.13	2.28
	0,4	40.2	9:164	2.52	1.93
	4,6	4.47	4:160	3.43	2.42
13–31	0,1	22.8	3:159	3.89	2.67
	1,2	12.6	5:154	3.14	2.28
	2,3	4.91	5:149	3.14	2.28
	0,4	17.3	9:153	2.52	1.93
	4,5	4.55	4:149	3.44	2.42

TABLE 13–57. *"F" values for significance of reduction of variance due to added variables*—Continued

Table	Equation*	"F" ratio	D.F.**	Critical "F" Ratio	
				α = 0.01	α = 0.05
13–34	0,1	22.5	7:172	2.75	2.07
	1,2	3.38	3:169	3.88	2.67
	0,3	19.4	8:169	2.62	2.00
	3,4	3.76	3:168	3.88	2.67
13–35	0,1	20.8	8:159	2.62	2.00
	1,2	2.72	3:156	3.89	2.67
	0,3	20.9	8:159	2.62	2.00
	3,4	3.12	3:156	3.89	2.67
13–38	0,1	18.8	8:163	2.62	2.00
	1,2	3.23	3:160	3.88	2.67
	0,3	18.6	8:163	2.62	2.00
	3,5	3.51	3:160	3.88	2.67
13–39	0,1	18.0	9:151	2.53	1.93
	1,2	2.30	3:148	3.90	2.67
	0,3	17.8	9:151	2.53	1.93
13–42	0,1	26.2	9:170	2.52	1.93
	1,2	3.70	4:166	3.43	2.42
	0,3	29.0	8:171	2.62	2.00
	3,4	3.10	4:167	3.43	2.42
13–43	0,1	23.7	9:158	2.52	1.93
	1,2	3.84	4:154	3.44	2.42
	0,3	26.5	8:159	2.62	2.00
	3,4	3.23	4:155	3.44	2.42
13–46	0,1	23.8	9:163	2.52	1.93
	1,2	6.78	1:162	6.77	3.90
	0,3	25.5	9:163	2.52	1.93
	3,4	4.20	3:160	3.88	2.67
	0,5	28.7	8:164	2.62	2.00
	5,6	4.22	3:161	3.88	2.67
13–47	0,1	21.8	9:152	2.53	1.93
	1,2	5.21	1:151	6.78	3.90
	0,3	23.2	9:152	2.53	1.93
	3,4	4.25	3:149	3.90	2.67
	0,5	26.5	8:153	2.62	2.00
	5,6	4.38	3:150	3.90	2.67
13–50	0,1	14.0	8:161	2.62	2.00
	1,2	7.0	4:157	3.43	2.42
	0,3	19.6	6:163	2.92	2.15
	3,4	6.55	4:159	3.43	2.42
13–51	0,1	11.6	8:149	2.62	2.00
	1,2	6.74	4:145	3.44	2.42
	0,3	15.8	6:151	2.92	2.15
	3,4	6.26	4:147	3.44	2.42
13–54	0,1	12.6	8:155	2.62	2.00
	1,2	4.59	5:150	3.14	2.28
	0,3	14.8	7:156	2.75	2.07
	3,4	4.00	6:150	2.92	2.15
13–55	0,1	10.2	8:144	2.62	2.00
	1,2	4.84	5:139	3.15	2.28
	0,3	11.9	7:145	2.76	2.07
	3,4	4.21	6:139	2.93	2.15

*Equation 0 refers to the variance for the values themselves with no fitted equation.

**D.F. = degrees of freedom. Numbers preceding and following the colon refer to degrees of freedom for the numerator and denominator of the "F" ratio, respectively.

7. Discussion

7.1. Independent Variables Associated with the Dynamic Modulus of Elasticity

One equation selected from each of the tables of equations representing Series O concretes made of AE + NAE cements is presented in table 13–58, columns 1, 2, 3, and 4, to facilitate a comparison of the independent variables associated with the dynamic modulus at the different ages and test conditions. The ratios of the dynamic modulus values at the different ages and curing conditions are presented in columns 5, 6, and 7 of this table. The coef./s.d. values of the independent variables and the calculated ranges of contributions to the dynamic modulus and the ratios are also presented in this table.

Higher air contents were associated with lower dynamic modulus values at all ages and conditions (columns 1, 2, 3, and 4). Higher air contents were associated with higher values of both the ratios involving soaking, but there was no evidence of a relationship with the OE70/14 ratio involving drying. It was previously noted in part 3 section 7 table 7–77 that an increase in the air content was associated with a decrease of compressive strength at all ages [18].

The coefficient for C_3A was significant and negative after the 56-day drying period (col 3) and after the 28 days in water (col 4) as well as for the three ratios (cols 5, 6, and 7). It was noted in section 7 that C_3A was associated with lower compressive strengths at the later ages [18].

The coefficient for C_3S was positive and highly significant at each of the test conditions. This was also true with respect to the compressive strength of mortar cubes at early ages in section 7 [18]. In column 6, the coefficient for C_3S was negative and highly significant.

The coefficient for C_4AF was negative and significant at each of the test conditions (cols 1, 2, 3, and 4). No evidence was found for a strong correlation with the compressive strength in section 7 [18].

The coefficient for SO_3 was positive and highly significant at each of the test conditions (cols 1, 2, 3, and 4) and also for the OE70/14 ratio (col 5). The coefficient for C_3A/SO_3 was positive and highly significant for the OE98/70 and OE71/70 ratios. The SO_3 was also positive in the equations for 1, 3, and possibly 7-day compressive strength of 1:2.75 (cement to sand) mortar cubes in section 7 [18] and also for the equation for the cubes stored in air.

The coefficient for Na_2O was positive and significant at 14 days in the dynamic tests (col 1). This differs from the results of static strength tests (See part 4, section 7) where there was no evidence of a relationship at the early ages, but at 1, 5, and 10 years the coefficient had a negative sign. The coefficients for K_2O were not highly significant in the dynamic tests but were probably significant at early ages in the compressive strength tests [18].

An increase in fineness was associated with a decrease in dynamic modulus after 28 and 56 days drying and 28 days resoaking. As previously indicated in part 3 section 7, an increase in fineness was associated with an increase of compressive strength of mortar cubes [18].

The coefficient for loss-on-ignition was positive in the equation for the dynamic modulus after 8 weeks of drying (col 3) and was also significant but with a negative sign in cols 5, 6, and 7 with the ratios for the different conditions. Higher loss-on-ignition was associated with lower compressive strength of mortar cubes at the early ages [18].

In general the coefficients for the trace elements were not highly significant. Of the 19 included in table 13–58, 8 had coef./s.d. ratios of 2.0 or greater, and one of these (Zr in col. 7) was greater than 3.0.

Equations for the Series A concretes made with a slump of 5 ± 1-in are presented in table 13–59. An increase of the amount of water required to obtain the desired slump was associated with lower dynamic-modulus values at each of the test conditions. It has previously been indicated in part 1, section 2 [16] that the water/cement ratio is also a function of the properties of the cements. Thus, interaction of this variable with other so-called independent variables of the equations is a possibility. In general, the differences in air content, w/c, C_3S, and SO_3 of the cements of the Series A concretes had the greatest effect on the calculated ranges of contributions after 14 days moist curing and after both 4 and 8 weeks of drying (cols 1, 2, and 3), and an increase of C_3A was associated with lower strengths after the 28 days in water (col 4).

7.2. Effect of Trace Elements

Evidence from many of the previous tables in this section, especially those dealing with the wet specimens, shows that the additional use of the trace elements in an equation generally caused a significant reduction in variance. After 4 or 8 weeks drying there was no evidence that the trace elements had a significant effect. (See tables 13–10, 13–11, 13–14, 13–15, 13–18, 13–19, 13–22, 13–23, and 13–57.) In equations for the ratios, inclusion of the trace elements resulted in a more significant reduction of variance for the AE71/70 and OE71/70 ratios, and somewhat less for the 98/70-day ratio. There were more instances of questionable significance for the 70/14-day ratios of dynamic modulus values.

TABLE 13–58. *Coefficients, coef./s.d. ratios, and calculated ranges of contributions of independent variables associated with the dynamic modulus values of Series O concretes at various ages*

Column	1	2	3	4	5	6	7
Eq. No.	2	2	2	2	2	2	2
Table No.	13-2	13-10	13-18	13-26	13-34	13-42	13-50
Dependent variable	OD14	OD42	OD70	OD98	OE70/14	OE98/70	OE71/70
	=	=	=	=	=	=	=
Constant	+3.723	+3.665	+3.523	+5.25	+0.880	+1.374	+1.046
Air content, coef.	−0.1593	−0.1549	−0.1567	−0.1400		+0.0101	+0.00435
Coef./s.d.	20.7	19.9	19.8	26.9		5.3	5.3
Calculated range	1.59	1.55	1.57	1.40		0.101	0.044
C_3A, coef.	+0.01007	−0.0086	−0.0256	−0.0152	−0.00587	−0.0178	−0.00412
Coef./s.d.	1.7	1.5	4.1	3.7	6.9	7.4	4.1
Calculated range	0.14	0.12	0.36	0.21	0.082	0.249	0.058
C_3S, coef.	+0.0196	+0.0168	+0.0181	+0.00601		−0.00411	−0.000413
Coef./s.d.	9.3	7.3	7.9	3.9		7.8	1.8
Calculated range	0.88	0.76	0.81	0.27		0.185	0.018
C_4AF, coef.	−0.0178	−0.0224	−0.0302	−0.0142		+0.00261	
Coef./s.d.	2.4	2.9	3.9	2.7		1.4	
Calculated range	0.25	0.31	0.42	0.20		0.036	
SO_3, coef.	+0.160	+0.507	+0.551	+0.183	+0.0698		
Coef./s.d.	3.9	10.3	7.9	5.4	8.0		
Calculated range	0.32	1.01	1.10	0.37	0.134		
C_3A/SO_3, coef.						+0.0339	+0.00702
Coef./s.d.						8.1	3.8
Calculated range						0.829	0.068
Na_2O, coef.	+0.260	+0.210			−0.0385		
Coef./s.d.	3.2	2.5			2.6		
Calculated range	0.18	0.15			0.027		
K_2O, coef.	+0.148		−0.102			−0.0495	−0.0213
Coef./s.d.	1.9		1.3			2.8	2.8
Calculated range	0.16		0.11			0.054	0.023
MgO, coef.	+0.0240	+0.0246	+0.0308		+0.00225		−0.00215
Coef./s.d.	1.9	2.0	2.4		1.1		1.6
Calculated range	0.12	0.12	0.15		0.011		0.011
APF, coef.		−0.000099	−0.000128	−0.000078	−0.0000170		
Coef./s.d.		3.0	3.5	3.8	2.9		
Calculated range		0.30	0.38	0.23	0.051		
Loss, coef.			+0.116	−0.0361	−0.0259	−0.0232	−0.0165
Coef./s.d.			4.1	1.9	5.1	8.6	5.9
Calculated range			0.35	0.11	0.078	0.070	0.050
Ba, coef.				−0.663			
Coef./s.d.				2.8			
Calculated range				0.13			
Co, coef.						−8.18	−2.07
Coef./s.d.						1.8	2.0
Calculated range						0.081	0.021
Cu, coef.		−8.284		−2.84			
Coef./s.d.		2.0		2.1			
Calculated range		0.16		0.12			
Li, coef.						−2.53	
Coef./s.d.						2.5	
Calculated range						0.051	
Mn, coef.	−0.188				+0.0324		−0.0199
Coef./s.d.	1.6				1.6		1.6
Calculated range	0.19				0.032		0.020
Ni, coef.							−0.898
Coef./s.d.							2.0
Calculated range							0.018
P, coef.						+0.0506	
Coef./s.d.						1.7	
Calculated range						0.025	
Rb, coef.	+18.63				−2.14		
Coef./s.d.	2.4				1.6		
Calculated range	0.19				0.021		
V, coef.			−1.019				
Coef./s.d.			1.2				
Calculated range			0.10				
Zr, coef.	+0.561			+0.619	−0.134	+0.162	+0.130
Coef./s.d.	1.7			2.7	2.1	1.9	3.6
Calculated range	0.28			0.82	0.067	0.081	0.065

TABLE 13–59. *Coefficients, coef./s.d. ratios, and calculated ranges of contributions of independent variables associated with the dynamic modulus values of Series A concretes at various ages*

Column	1	2	3	4	5	6	7
Eq. No.	5	5	5	3	2	4	2
Table No.	13-6	13-14	13-22	13-30	13-38	13-46	13-54
Dependent variable	AD14	AD42	AD70	AD98	AE70/14	AE98/70	AE71/70
	=	=	=	=	=	=	=
Constant	+7.870	+7.766	+6.621	+9.589	+0.905	+1.333	+1.038
Air content, coef.	−0.1406	−0.1260	−0.1235	−0.1285		+0.00491	+0.00399
Coef./s.d.	12.7	9.7	9.8	16.1		3.2	5.9
Calculated range	1.83	1.64	1.61	1.67		0.064	0.052
w/c, coef.	−6.435	−6.649	−5.356	−6.795			
Coef./s.d.	6.9	5.9	4.9	9.8			
Calculated range	1.09	1.13	0.91	1.16			
C_3A, coef.		−0.0102	−0.0336	−0.0179	−0.00714	−0.01555	−0.00454
Coef./s.d.		1.5	4.9	4.2	6.9	6.9	4.6
Calculated range		0.14	0.47	0.25	0.104	0.218	0.063
C_3S, coef.	+0.0190	+0.0173	+0.0183	+0.00475		−0.00376	−0.000382
Coef./s.d.	9.0	6.7	7.3	3.1		7.7	1.8
Calculated range	0.86	0.78	0.82	0.21		0.169	0.017
C_4AF, coef.	−0.0273	−0.0193	−0.0299	−0.0166	−0.00173	+0.00325	
Coef./s.d.	4.3	2.9	3.6	3.2	1.3	1.9	
Calculated range	0.38	0.27	0.42	0.23	0.024	0.045	
SO_3, coef.	+0.211	+0.508	+0.532	+0.204	+0.0722		
Coef./s.d.	5.0	2.3	9.3	5.8	8.0		
Calculated range	0.42	1.02	1.06	0.40	0.144		
C_3A/SO_3, coef.						+0.0356	+0.00811
Coef./s.d.						8.9	4.5
Calculated range						0.345	0.079
Na_2O, coef.	+0.270				−0.0434		
Coef./s.d.	3.4				2.95		
Calculated range	0.19				0.030		
K_2O, coef.	+0.222		+0.249			−0.0632	−0.0295
Coef./s.d.	3.0		3.0			3.9	3.4
Calculated range	0.24		0.27			0.070	0.32
MgO, coef.	+0.0226	+0.0348	+0.0349		+0.0037	−0.00716	−0.00328
Coef./s.d.	1.8	2.5	2.6		1.8	2.5	2.4
Calculated range	0.11	0.17	0.17		0.019	0.036	0.016
APF, coef.		−0.000104	−0.000088	−0.000051	−0.0000166		
Coef./s.d.		2.7	2.3	2.3	2.8		
Calculated range		0.31	0.26	0.15	0.050		
Loss, coef.		+0.0452	+0.0951		+0.0203	−0.0172	−0.00882
Coef./s.d.		1.4	3.1		4.0	2.9	3.2
Calculated range		0.14	0.28		0.061	0.052	0.026
Ba, coef.				−0.428			
Coef./s.d.				1.5			
Calculated range				0.09			
Co, coef.					+2.59	−3.22	−1.85
Coef./s.d.					1.5	1.5	1.8
Calculated range					0.026	0.032	0.018
Cu, coef.		−4.41		−3.02			
Coef./s.d.		2.3		2.7			
Calculated range		0.22		0.15			
Li, coef.		+9.11	+7.07			−2.19	−0.743
Coef./s.d.		2.0	1.6			2.4	1.7
Calculated range		0.18	0.14			0.043	0.014
Ni, coef.							−0.978
Coef./s.d.							2.2
Calculated range							0.020
Mn, coef.	−0.185				+0.0396		
Coef./s.d.	1.7				1.9		
Calculated range	0.18				0.040		
P, coef.					+0.0667		
Coef./s.d.					2.3		
Calculated range					0.033		
Rb, coef.	+14.86			+8.60	−2.45		+1.84
Coef./s.d.	1.9			1.7	1.8		2.1
Calculated range	0.15			0.09	0.024		0.018
Ti, coef.				−0.165			
Coef./s.d.				2.1			
Calculated range				0.16			
Zr, coef.		+0.381		+0.541			−0.0580
Coef./s.d.		1.0		2.4			1.7
Calculated range		0.19		0.27			0.029

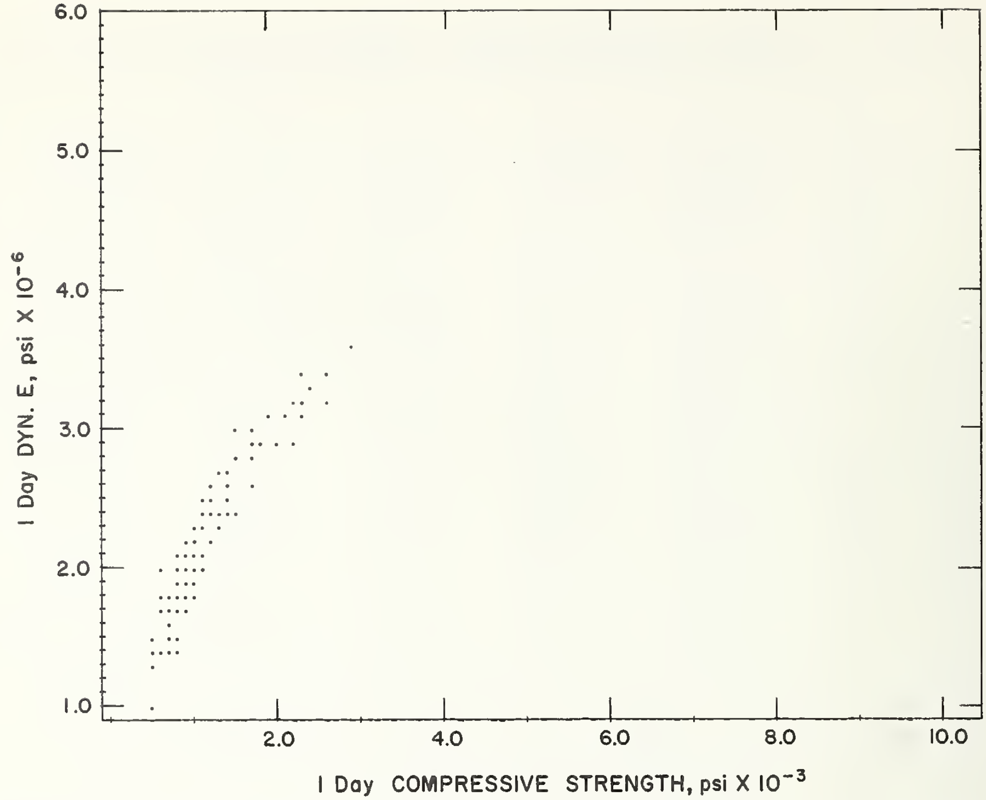

FIGURE 13–1. *Dynamic Young's modulus of elasticity at 1 day versus the 1-day compressive strength of 1:2.75 (cement to graded Ottawa sand) mortars.*

7.3. Relationships of Dynamic Modulus to Various Characteristics of Mortar Bars

Investigation was made of the relationship between 14-day dynamic modulus of the concretes and the following characteristics of 4- × 4- × 16-cm mortar bars made with the same cements: (1) 7-day dynamic modulus of the bars, (2) modulus of rupture of the bars, and (3) compressive strengths of modified cubes from the ruptured bars. In none of these cases was a significant relationship found.

Relationships between dynamic modulus, compressive strength, and modulus of rupture of the 4- × 4- × 16-cm mortar prisms at 1, 3, and 7 days age are presented graphically in figures 13–1 through 13–9. The first three figures show relationships between dynamic modulus and compressive strength at the three ages. Figures 13–4 through 13–6 show dynamic modulus versus modulus of rupture, and figures 13–7 through 13–9 show compressive strength versus modulus of rupture.

Highly significant relationships evidently exist between these three variables when measured on the same specimens. The relationships appear to be nonlinear, however.

7.4. Compressive and Flexural Tests of Concretes

No compressive or flexural strengths of these concretes were determined at the time the cements were tested. At the age of 7 years, 24 pairs of 3- × 4- × 16-in specimens were removed from the field exposure and placed in water for 28 days. Then resonant frequency and flexural and compressive strengths were determined on one of the beams. The compressive strengths were determined on 3- × 3- × 4-in prisms sawed from the broken beams. No correction was made for the nonstandard shape and height-width ratio of the specimens. The specimens selected were all from concretes which had the same w/c for the Series O and Series A concretes.

The average dynamic modulus of elasticity was 5.58×10^6 psi with a range of values from 4.95 to 5.96×10^6 psi. The average compressive strength was 4350 psi with a range of 3040 to 5660 psi The average modulus of rupture was 624 psi with a range of 490 to 770 psi. The trends of the relationships are indicated by the dashed lines in figures 13–10 and 13–11. No trend line was placed in figure 13–12 showing the relationship of compressive to flexural strengths because of the broad

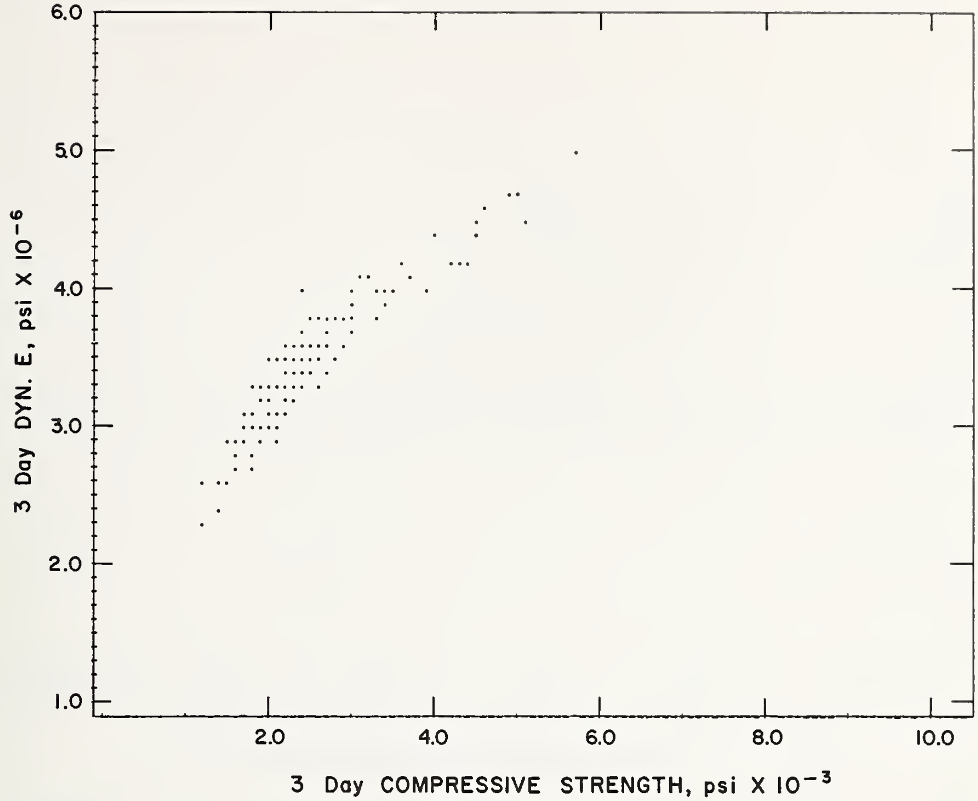

FIGURE 13–2. *Dynamic Young's modulus of elasticity at 3 days versus the 3-day compressive strength of 1:2.75 (cement to graded Ottawa sand) mortars.*

scatter of results. The ranges of values of the concretes selected for these tests were much less than those of the 1-, 3-, and 7-day mortar tests in Figures 13–1 through 13–9, and this makes it more difficult in the case of concretes to establish overall trends.

7.5. Effect of Drying and Resoaking on Dynamic Modulus of Concretes

The average dynamic-modulus values and averages of the ratios for 70/14-, 98/70-, and 71/70-day dynamic-modulus values have been presented in the tables of equations. There was an average reduction of dynamic modulus of 7 percent when the specimens were dried for 8 weeks, an average increase of dynamic modulus of 15 percent when the dried specimens were placed in water for 28 days. When the air-dried specimens were placed in water for 24 hours the average dynamic modulus for all specimens was about 1 percent less than when measurements were made on the dry specimens.

However, consideration must be given to the broad distribution of values for all of the ratios as it was evident that concretes made of the different cements behaved quite differently. Drying and wetting can produce tensile and compressive stresses in a concrete specimen and these may be factors affecting the fundamental resonant frequencies of the specimens. Soaking the air-dried specimens in water for 24 hours resulted in as much as 5-percent reduction in dynamic modulus for some specimens and in others, up to a 5-percent increase in dynamic modulus. It has previously been noted that the saturation ratio (part 5 section 11) also varied with concretes made of different cements. Whereas some specimens were about 80 percent saturated in 24 hours, others were only about 20 percent saturated. The slight reduction in dynamic modulus with 24 hours of resoaking of the air-dried specimens of some of the cements may have resulted from a relief of possible tensile stresses on the skin of the specimens whereas the slight increase may have resulted from the filling of the voids.

One of the contributing factors to the 70/14-day ratio was undoubtedly the continued hydration which occurred during the 56-day storage in laboratory air. The rate of hydration may have been different for concretes made with different cements. The loss of different quantities of water

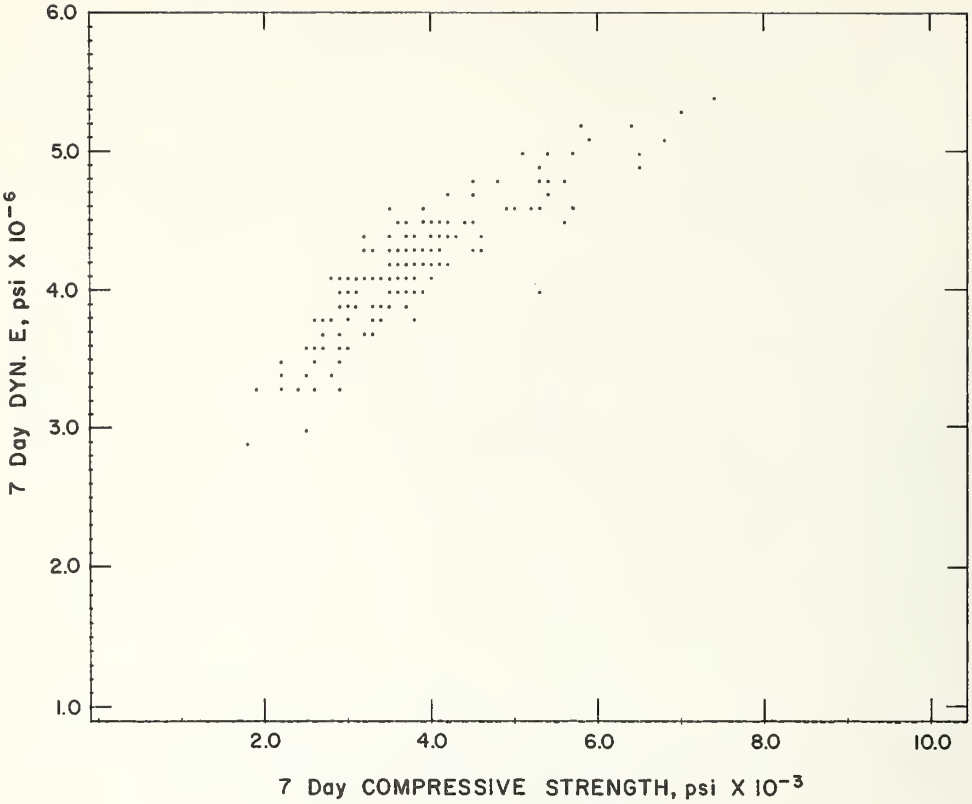

FIGURE 13-3. *Dynamic Young's modulus of elasticity at 7 days versus the 7-day compressive strength of 1:2.75 (cement to graded Ottawa sand) mortars.*

as indicated in section 12 would result in differences of the voids of the different concretes.

It was noted that the 98/70-day ratios were all greater than 1.0 but there was a broad distribution of values. The extent of filling of the pore structure plus continued hydration could account for the increase in dynamic modulus and for some of these differences.

When concrete specimens are exposed to outdoor weathering, the dynamic modulus of elasticity may be affected by the moisture condition and moisture distribution within the specimens. Unless there are gross differences in dynamic properties there would be the uncertainty of the role of the moisture condition. If specimens are kept moist prior to measurement there is, as indicated in section 11, a possibility of autogenous healing. Measurements made on the specimens stored outdoors indicated a slight (perhaps significant) increase in dynamic modulus in the fall as compared to measurements made in the spring after the winter freezing and thawing exposure. Factors other than normal weathering may have been responsible.

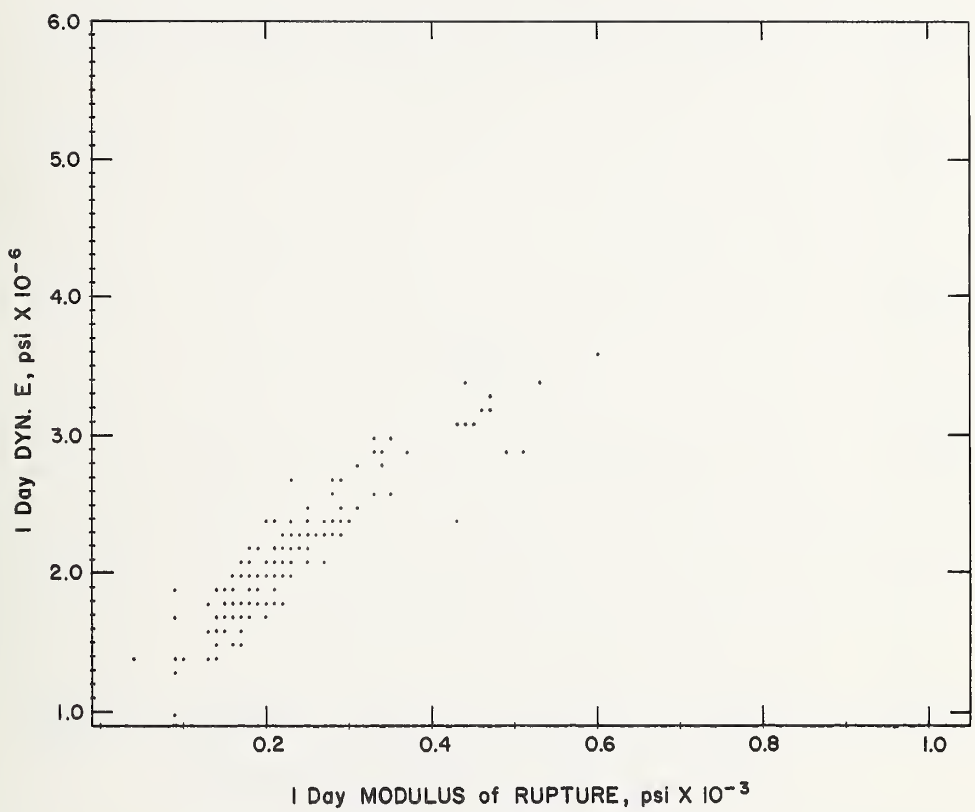

FIGURE 13–4. *Dynamic Young's modulus of elasticity at 1 day versus the 1-day modulus of rupture of 1:2.75 (cement to graded Ottawa sand) mortars.*

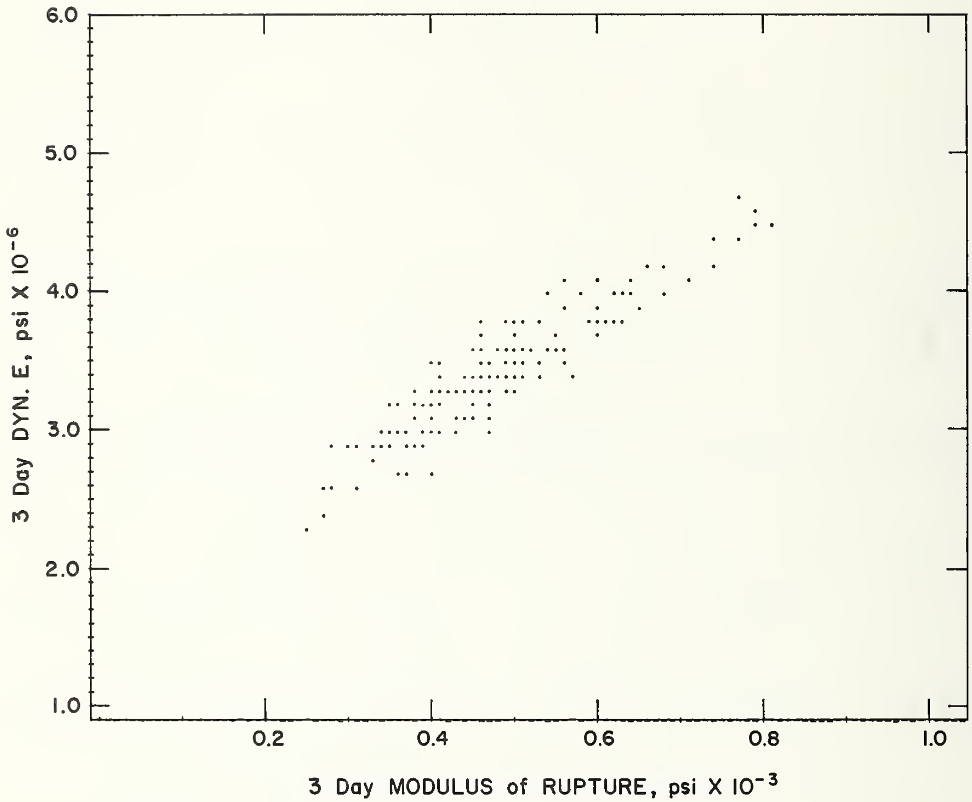

FIGURE 13–5. *Dynamic Young's modulus of elasticity at 3 days versus the 3-day modulus of rupture of 1:2.75 (cement to graded Ottawa sand) mortars.*

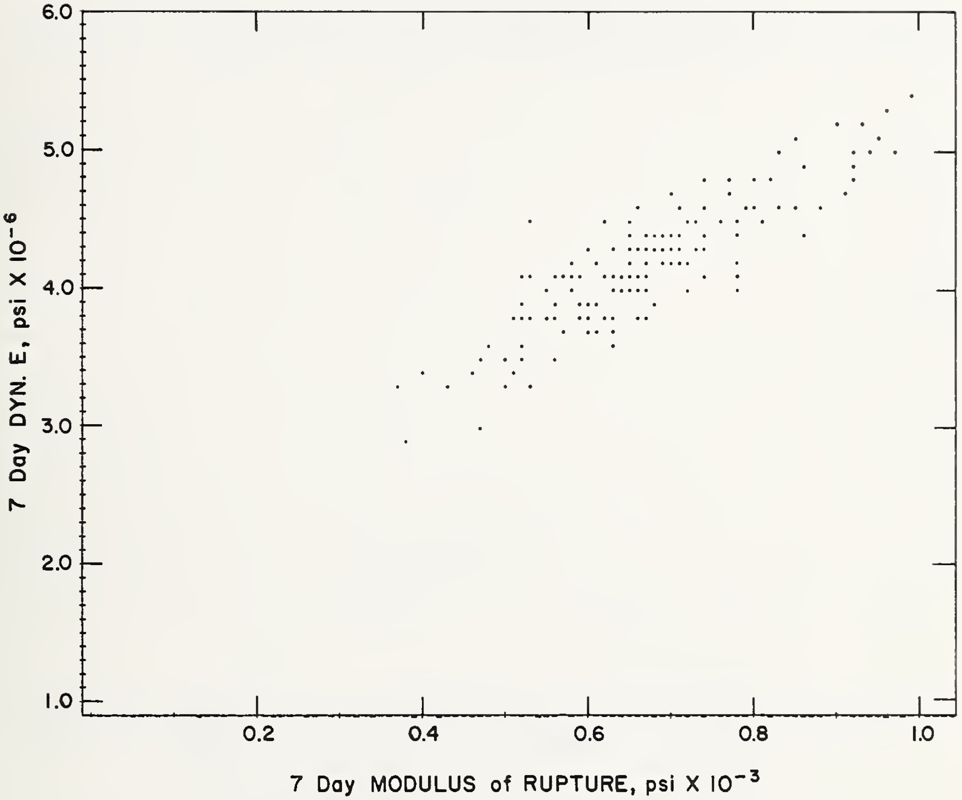

FIGURE 13–6. *Dynamic Young's modulus of elasticity at 7 days versus the 7-day modulus of rupture of 1:2.75 (cement to graded Ottawa sand) mortars.*

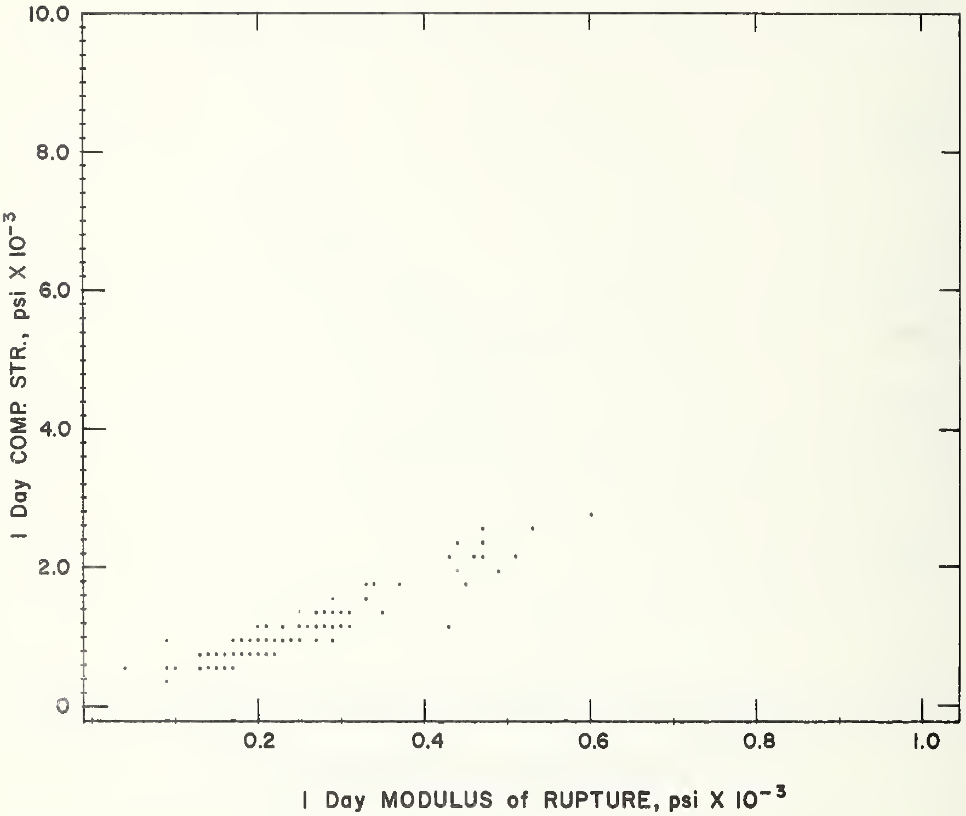

FIGURE 13–7. *Compressive strength at 1 day versus the modulus of rupture at 1 day of 1:2.75 (cement to graded Ottawa sand) mortars.*

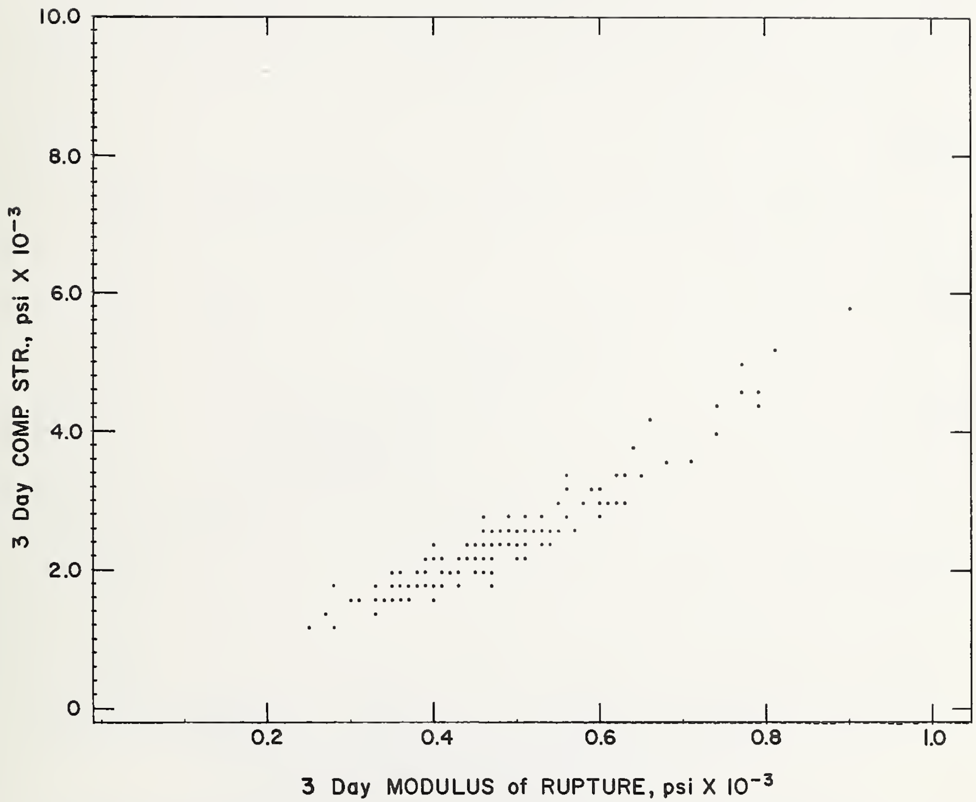

FIGURE 13–8. *Compressive strength at 3 days versus the 3-day modulus of rupture of 1:2.75 (cement to graded Ottawa sand) mortars.*

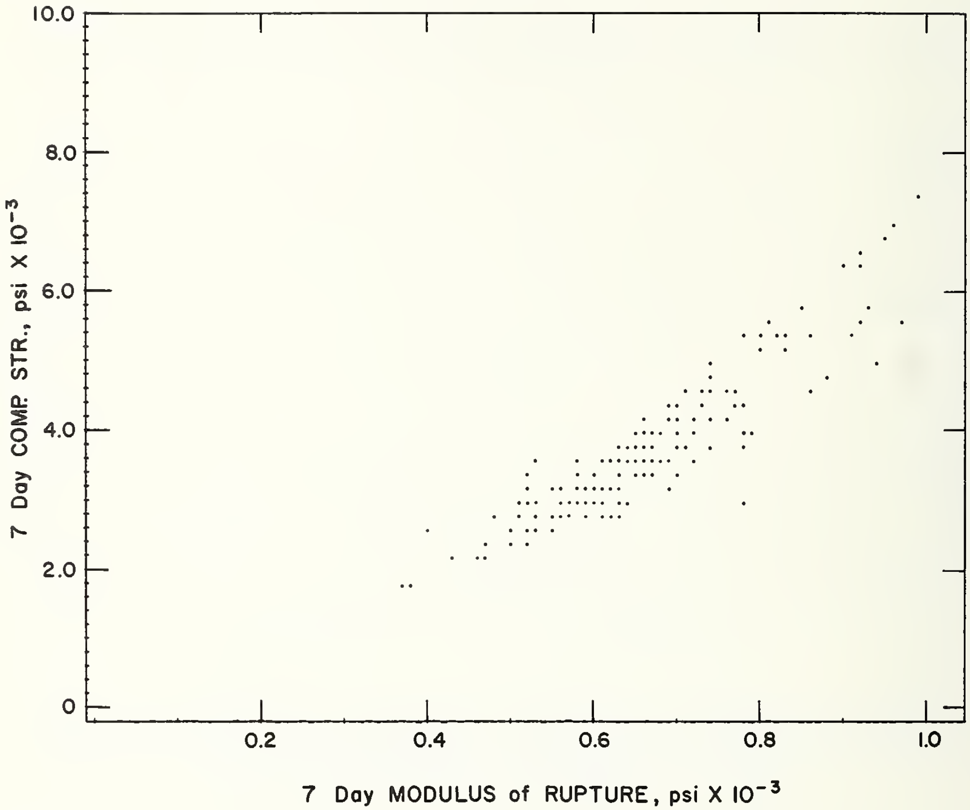

FIGURE 13–9. *Compressive strength at 7 days versus the 7-day modulus of rupture of 1:2.75 (cement to graded Ottawa sand) mortars.*

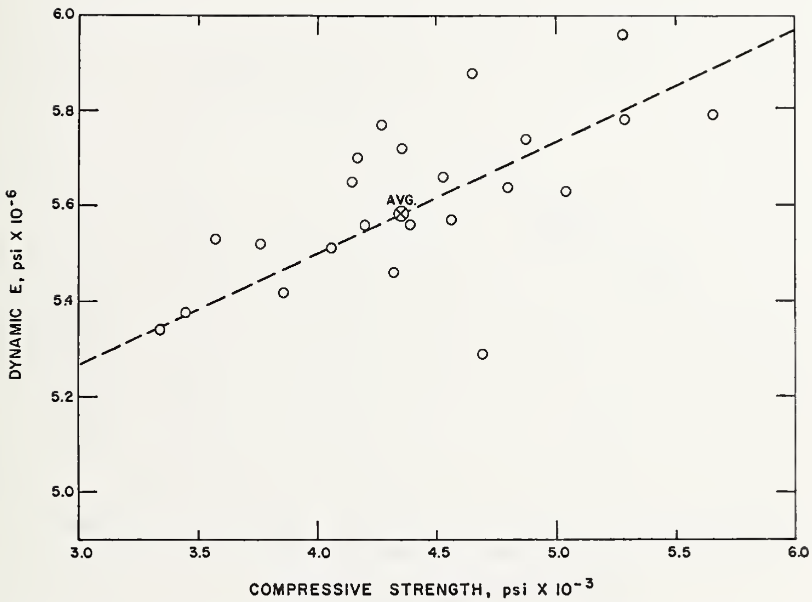

FIGURE 13–10. *Dynamic Young's modulus of elasticity of concretes versus the compressive strength at 7 years after outdoor storage.*

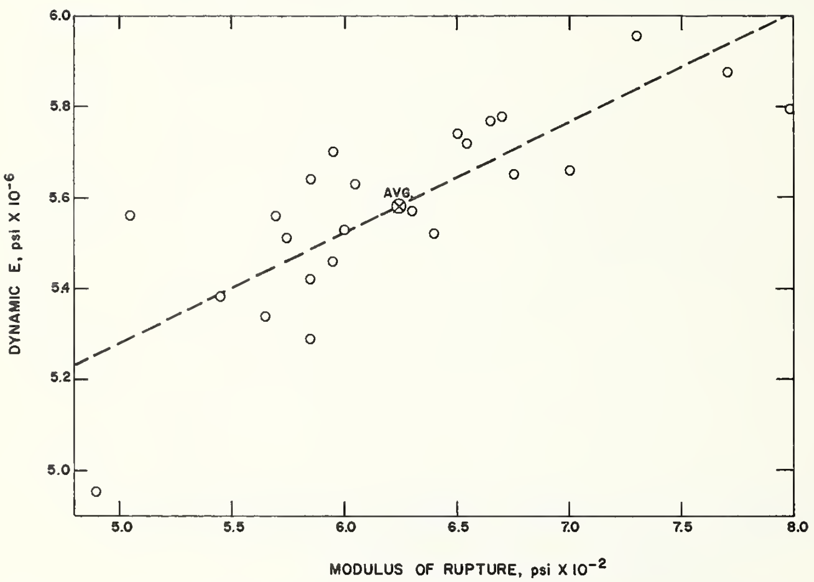

FIGURE 13–11. *Dynamic Young's modulus of elasticity of concretes versus the modulus of rupture at 7 years after outdoor exposure.*

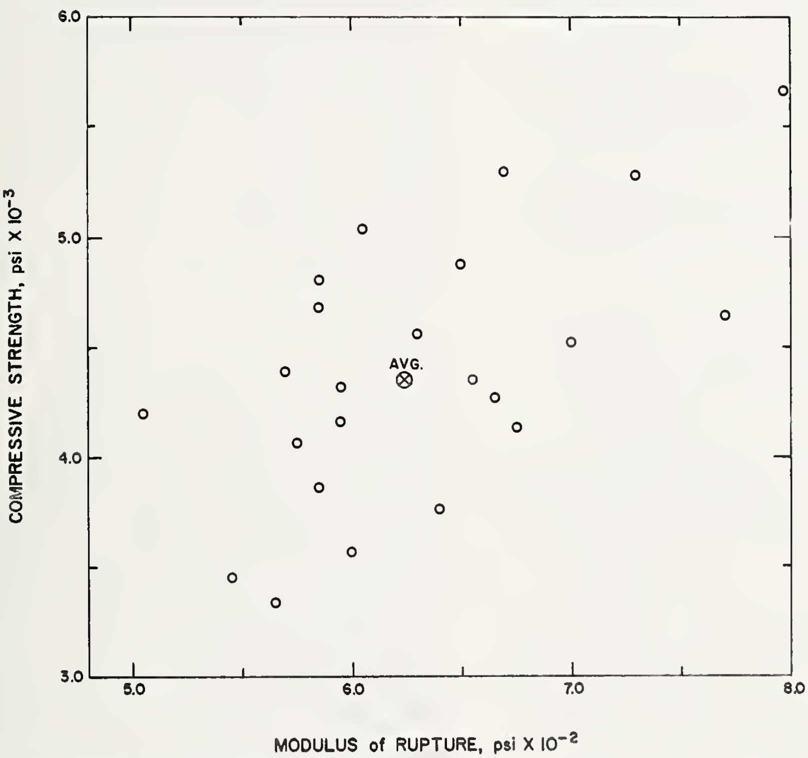

FIGURE 13–12. *Compressive strength of concretes versus the modulus of rupture at 7 years after outdoor exposure.*

8. Summary and Conclusions

(1) Measurements were made of the dynamic Young's modulus of elasticity of concretes made with 199 portland cements from different mills. One series of concretes (Series O) was made using a water/cement ratio of 0.635 and the other series (Series A) with the quantity of water adjusted to give a slump of 5 ± 1 in. A nominal quantity of 5.5 bags of cement per cubic yard was used. The 3- × 4- × 16-in specimens were moist cured for 14 days, dried in laboratory air for 8 weeks, then placed in water for 4 weeks. The fundamental transverse frequency was determined at 14, 42, 70, 71, and 98 days. The ratios of the dynamic modulus values at 70/14, 98/70, and 71/70 days were computed.

(2) The dynamic modulus after 14 days moist curing ranged from 3.4 to 5.8 × 10^6 psi, with an average of 4.75 × 10^6 psi for the Series O concretes amd 4.76 × 10^6 psi for the Series A concretes.

(3) After drying in laboratory air for 4 weeks there was an average reduction of about 4 percent in the dynamic modulus. There was, however, a broad distribution of values.

(4) After drying in laboratory air for 8 weeks there was an average reduction of 7 percent in dynamic modulus. Concretes made with some of the cements showed an increase in dynamic modulus during the drying period, possibly due to continued hydration.

(5) When the concrete specimens which had been air-dried for 8 weeks were placed in water for 24 hours, the dynamic modulus of some decreased up to 5 percent and others increased up to 5 percent.

(6) When the concrete specimens which had been air-dried for 8 weeks were placed in water for 4 weeks, there was an average of 15 percent increase in dynamic modulus. There was a broad distribution of values. Some concretes increased only about 5 percent, and others had a 40-percent increase in dynamic modulus.

(7) Computations of multivariable equations by a least-squares method were used to investigate what chemical and physical properties of the cements and concretes were associated with the dynamic modulus of elasticity at the various ages, and with the ratios of the dynamic *E* at the various ages after the different curing conditions. The equations were computed for all the cements for which minor constituents and trace elements had been determined. The equations were computed using as independent variables, either the major potential compounds, or the major oxides, each with other commonly determined variables and these with trace elements found to be significant.

The following observations relate to equations as summarized in tables 13–58 and 13–59 for concretes made of AE + NAE cements using a water/cement ratio of 0.635 and concretes having a slump of 5 ± 1 inches respectively:

(7.1) An increase in the air content for both series of concretes and the water/cement ratio required to produce a concrete of the desired slump for the Series A concretes was associated with a decrease of the dynamic modulus at all conditions. An increase in the air content was associated with an increase of the OE98/70 (28-day soaking) and OE71/70-day (1-day soaking) ratios of dynamic modulus for both series.

(7.2) An increase of C_3A was associated with a decrease of the dynamic modulus after the 8-week drying period and after the subsequent 4 weeks in water. An increase in C_3A was also associated with a decrease of the dynamic modulus ratios, 70/14-day, 98/70-day, and 71/70-day.

(7.3) An increase of C_3S was associated with an increase of the dynamic modulus at all conditions and with a decrease of the 98/70-day ratio.

(7.4) An increase of C_4AF was generally associated with a decrease of the dynamic modulus at all conditions although there were a number of instances where the coef./s.d. ratio was less than 3.0.

(7.5) An increase of SO_3 was associated with an increase of the dynamic modulus at all conditions and with the 70/14-day ratio. An increase of C_3A/SO_3 was associated with an increase of the 98/70-day and 71/70-day ratios of dynamic modulus. The C_3A/SO_3 ratio interacts with the coefficients for C_3A and SO_3 and all must be taken into consideration in evaluating the effect.

(7.6) An increase in Na_2O was associated with an increase of the dynamic modulus after 14 days moist curing and possibly with a decrease of the 70/14-day ratio.

(7.7) An increase in K_2O was associated with an increase of the dynamic modulus after 14 days moist curing and after the 8-week drying period for the Series A concretes. The coefficient was of doubtful significance for the Series O concretes.

(7.8) An increase in MgO is probably associated with an increase in dynamic modulus after 4 and 8 weeks of drying.

(7.9) An increase of air-permeability fineness was associated with a decrease of dynamic modulus after 4 and 8 weeks of drying and after the 4 weeks resoaking for the Series O concretes and probably for the Series A concretes.

(7.10) An increase of the loss on ignition of the cements was associated with an increase of the dynamic modulus after the 8-week drying period, and with a decrease in the ratios of dynamic modulus at all conditions.

(7.11) The use of trace elements having coef./s.d. ratios greater than 1.0 as independent variables, together with other commonly determined independent variables in equations, generally resulted in a significant reduction of variance when

the concrete was moist. After 4 or 8 weeks drying in laboratory air there was no evidence that the trace elements had a significant effect. With a few exceptions, the coefficients of the trace elements were of doubtful significance.

(8) The use of the major oxides instead of the major compounds, but with other commonly determined independent variables and trace elements, generally resulted in equations with about the same estimated standard deviation.

(9) Equations calculated for concretes made of the NAE cements resulted in coefficients, coef./s.d. ratios, and S.D. values in reasonable accord with those calculated for the concretes made of the AE + NAE cements.

(10) There was no significant relationship between the dynamic modulus of the concretes at 14 days and the dynamic modulus of 1:2.75 (cement to graded Ottawa sand) mortar prisms at 7 days.

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The concretes described in earlier parts of this series were subjected to laboratory freezing and thawing tests, and measurements were made of the weight loss, dynamic modulus, durability factor, and number of cycles required to reach 40 percent reduction in dynamic modulus. Companion specimens were subjected to drying and subsequent soaking in the laboratory and to dynamic modulus tests at various ages and moisture conditions. The effect on these properties of a large number of variables connected with chemical and physical properties of the cements and with properties of the concretes was studied by multivariable regression techniques. Air content of the concretes and degree of saturation generally had the greatest effect on the measurements. In general, minor constituents and trace elements did not show significant relationships with the measured properties, but there was evidence that some of the variables, such as alkali content, water cement ratio, slump, and possibly setting time might have influenced durability through an effect on the air-void system. Specimens stored in the fog room after the freezing-and-thawing tests generally regained most or all of their original dynamic modulus. There were significant differences between cements with respect to regain of dynamic modulus (autogenous healing), with the non-air-entrained cements gaining more than the air-entraining cements, on the average.

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